Prediction of Relative Density of Sand with Particular Reference to Compaction Energy

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Technology
in
Civil Engineering

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By

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Under the Guidance of

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Rourkela

CERTIFICATE

This is to certify that the thesis entitled, "**Prediction of relative density of sand with particular reference to compaction energy**" submitted by **Mr Shuvranshu Kumar Rout** in partial fulfillment of the requirements for the award of Master of Technology in Civil Engineering at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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Shuvranshu Kumar Rout

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Abstract

Field compaction of sands usually involves different equipments with the compaction energy varying significantly. The relative density is the better indicator for specifying the compaction of granular soil. If the relative density can be correlated simply by any index property of the granular soil, it can be more useful in the field. The relative density is defined in terms of voids ratio. It is well known that the minimum and maximum voids ratio depend on the mean grain size. However, there is no direct relation available for the voids ratio in terms of grain size. Therefore, in this dissertation, the effect of mean grain size on the relative density of sand has been studied at different compaction energies.

In order to arrive at the above, fifty five number of clean sands having D_{50} ranges from 0.34 to 2.6 mm collected from different river bed of Orissa have been tested in the laboratory. The various index properties like grain specific gravity, grain size distribution of all the samples have been determined. The minimum and maximum voids ratio have been determined. For determining minimum voids ratio; both wet and dry method have been adopted. The voids ratio corresponding to energy level of standard, modified, reduced standard, and reduced modified Proctor tests have been correlated with mean grain size and thus the simple nonlinear empirical relations have been developed. Similarly, the relative densities corresponding to the energy level of above mentioned Proctor tests also have been correlated with mean grain size to arrive at simple empirical equations. The percentage deviation of the relative density estimated by the proposed method is in the range of ± 5 % of the measured value. The above correlations of relative densities will be helpful for the design specifications in the field.

Key Words: Clean Sands, Compaction, Compaction Energy, Empirical Equations, Mean Grain Size, Relative Density, Void Ratio.

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List of Abbreviations and Symbols

Abbreviation

MDD	Maximum Dry Density
OMC	Optimum Moisture Content

Symbols

G	Specific Gravity
E	Energy
D_{50}	Mean Grain size (Grain size corresponding to 50 % finer)
D_{60}	Grain size corresponding to 60 % finer
D_{30}	Grain size corresponding to 30 % finer
D_{10}	Grain size corresponding to 10 % finer
C_u	Coefficient of Uniformity
C_c	Coefficient of Curvature
γ_d	Maximum Dry Unit Weight
$(\gamma_d)_s$	Maximum Dry Unit Weight corresponding to Standard Proctor Test
$(\gamma_d)_m$	Maximum Dry Unit Weight corresponding to Modified Proctor Test
$(\gamma_d)_{rs}$	Maximum Dry Unit Weight Reduced Standard Proctor Test
$(\gamma_d)_{rm}$	Maximum Dry Unit Weight Reduced Modified Proctor Test

e	Void Ratio
e_{max}	Maximum Void Ratio
e_{min}	Minimum Void Ratio
e_s	Void Ratio corresponding to Standard Proctor Test
e_m	Void Ratio corresponding to Modified Proctor Test
e_{rs}	Void Ratio corresponding to Reduced Standard Proctor Test
e_{rm}	Void Ratio corresponding to Reduced Modified Proctor Test
D_r	Relative Density
$(D_r)_s$	Relative Density corresponding to Standard Proctor Test
$(D_r)_m$	Relative Density corresponding to Modified Proctor Test
$(D_r)_{rs}$	Relative Density corresponding to Reduced Standard Proctor Test
$(D_r)_{rm}$	Relative Density corresponding to Reduced Modified Proctor Test
R_c	Relative Compaction

CHAPTER 1

INTRODUCTION

INTROUCTION

1.1 BACKGROUND

Compaction is a process of mechanical soil improvement; and is by far the most commonly used method of soil stabilization. Compaction is used to alter the engineering properties of a soil for a specific application, such as supporting a pavement section, building foundation, or bridge abutment etc. Density measurements are used in the field indirectly to gauge the effectiveness of the compaction process with an aim of improving soil behavior for the intended application. Compaction test is one of the tests that should be carried out before the other works started. The strength of soils is mostly dependent on types of soils, its density and its moisture content which can be obtained from compaction tests. The effectiveness of a compaction depends on few factors out of which compactive effort (types of equipment, weight of equipment, vibration, number of passes) is one of the factors that affects the compaction qualitatively. The main objective of the study is to find the effects of different compaction energy on the soil compaction parameters. Field compaction of sands usually involves different equipments with the compaction energy varying significantly. By comparing the different compaction energy, the standard Proctor and modified Proctor tests had been used to show the comparisons. Several activities have been identified to achieve the objectives, i.e., literature review, conducting tests in the laboratory, and analysing the results obtained from the laboratory tests. The Maximum Dry Density of soils increases when there is an increase in the compaction energy but the Optimum Moisture Content value decreases with increasing compaction energy/efforts. For cohesionless soils containing very little or no fines the water content has influence on the compacted density. At low water contents and particularly under a low compactive effort, density may decrease compared to that produced by the same compactive effort for air dried or oven dried soil. This decrease in density is due to the capillary tension which is not fully counteracted by compactive effort and which holds the particle in a loose state resisting compaction. Density reaches maximum when a cohesionless soil is fully saturated. Again, this maximum density may not be very much higher than that corresponding to the air or oven dried condition. Attainment of maximum density at full saturation should not be considered as due to the lubricating action of water but rather due to the reduction of effective pressure between soil particles by hydrostatic pressure. Hence the compaction characteristics (maximum dry unit weight and optimum moisture content) need to be obtained at different compaction energies. For cohesionless soil like sand it is better to express compaction behavior in terms of relative density. The relative density (D_r) of granular soils may be a better indicator for end-product compaction specifications than relative compaction. Thus knowledge of relative densities of sands at different compaction energies assumes great importance from the viewpoint of practical significance. Limit density values of sands should be regarded as important properties as the coefficient of uniformity (C_u), coefficient of curvature (C_c), mean particle size (D_{50}), and particle shape, among others, when providing a thorough description of sand. Density (or void ratio) limits help to more completely describe the material under consideration and are required when evaluating relative density of in-place soils. The maximum and minimum (limit) density values represent the theoretical upper and lower density boundaries for a given soil specimen (Holtz 1973). The maximum and minimum density values are among some of the most important properties to include when describing a sand specimen. Relative densities, maximum and minimum void ratio values of sand are greatly affected by particle shapes, sizes and their packing.

CHAPTER 2

LITERATURE REVIEW

2.1 THEORY OF RELATIVE DENSITY

Most significant property of cohesionless soil (granular soil) is relative density where as for cohesive soil is consistency. Relative density is the index property of a cohesionless soil. The engineering properties of a mass of cohesionless soil depend to a large extent on its relative density (D_r). Relative density is a term generally used to describe the degree of compaction of coarse-grained soils. The relative density is defined as

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \times 100 \tag{2.1}$$

where e = voids ratio in the natural state

e_{max} = maximum void ratio of the soil in the loosest condition

e_{min} = minimum void ratio of the soil in the densest condition

if $e = e_{min}$, $D_r = 100$ and the soil is in its densest state

$e = e_{max}$, $D_r = 0$ and the soil is in its loosest state

D_r varies from 0 to 100 always ($0 \leq D_r \leq 100$)

Relative density is generally expressed as a percentage. The relative density of a cohesionless soil gives a more clear idea of the denseness than does the void ratio. This quantity indicates the relative position of the field void ratio, e, between the maximum and minimum void ratios, e_{max} and e_{min}, for given sand. Two types of sand having the same void ratio may have entirely different state of denseness and engineering properties. The relative density of a soil indicates how it would behave under loads. If the deposit is dense, it can take heavy loads with very little settlements. Depending upon the relative density, the soils are generally divided into 5 categories (Table 2.1).

Table 2.1: Denseness of cohesionless soils (McCarthy, 2007)

Denseness	Very Loose	Loose	Medium Dense	Dense	Very Dense
D_r (%)	< 15	15 to 35	35 to 65	65 to 85	85 to 100

At any given void ratio the strength and compressibility characteristics of grannular soil is almost independent of the degree of saturation. The density of granular soil varies with its shape, size of the soil grains, gradation and the manner in which soil is compacted. If all the soil grains are assumed as spheres of uniform size then theoretically packed one are shown as in the Figure 2.1.

Loosest State

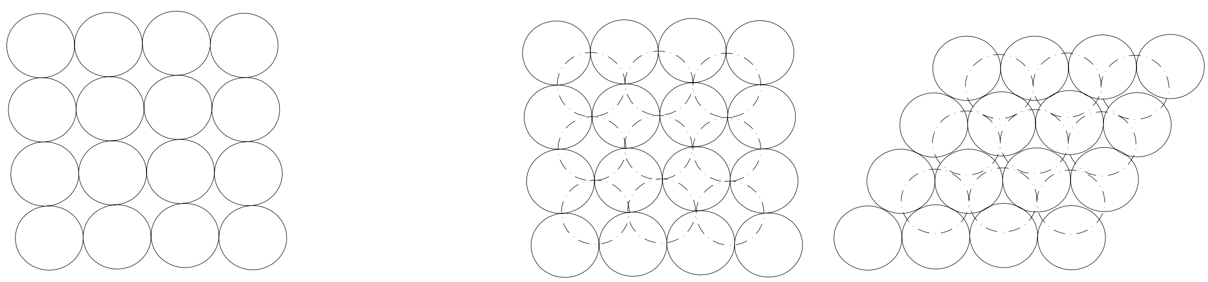
(Soil grains are one above another)

$$e = \frac{6 - \pi}{\pi} = 0.90986$$

Densest State

(Soil grains are in between two)

$$e = \frac{3\sqrt{2} - \pi}{\pi} = 0.35047$$



Cubical

Face-centered cubical (Pyramidal) or Close-packed hexagonal (Tetrahedral)

Figure 2.1 Theoretical packing of spherical particles

The soil corresponding to higher void ratio is in the loosest state and lower void ratio is in the densest state. If the soil grains are not uniform then the smaller grains fill in the space between the bigger ones and void ratio of such soils is reduced to e = 0.25. In the dense state if the soil grains are angular then they tend to form loosest structures than rounded grains because their sharp edges and points hold the grains further apart. But, if the soil mass with angular grains, is compacted by vibration then it forms a dense structure. A static load alone will not change the density of the grains significantly, but if it is accompanied by vibration there will be considerable increase in density. The water content in the void may act as lubricant to certain extent for increase in the density under vibration. Since the change in void ratio would change the density and this in turn will change the strength characteristics of granular soils. Void ratio or unit weight of the soil can be used to compare the strength characteristics of granular soils of the same origin. The properties and characteristic behavior patterns of granular materials are most often related to the relative density. So, the relative density is used to indicate the strength characteristics in qualitative manner. But, there are sudden practical difficulties in determining the void ratio. One of the problem involved lies in measuring the solid volume. So, in order to overcome this difficulty the relative density is expressed in terms of the dry unit weights associated with the various void ratios. They depend on various factors like soil type (mineralogy), particle grading, and angularity etc. In Figure 2.2 soils are in the densest, natural and loosest state. As it if difficult to measure the void ratio directly, it is convenient to express the void ratio in terms of dry density.

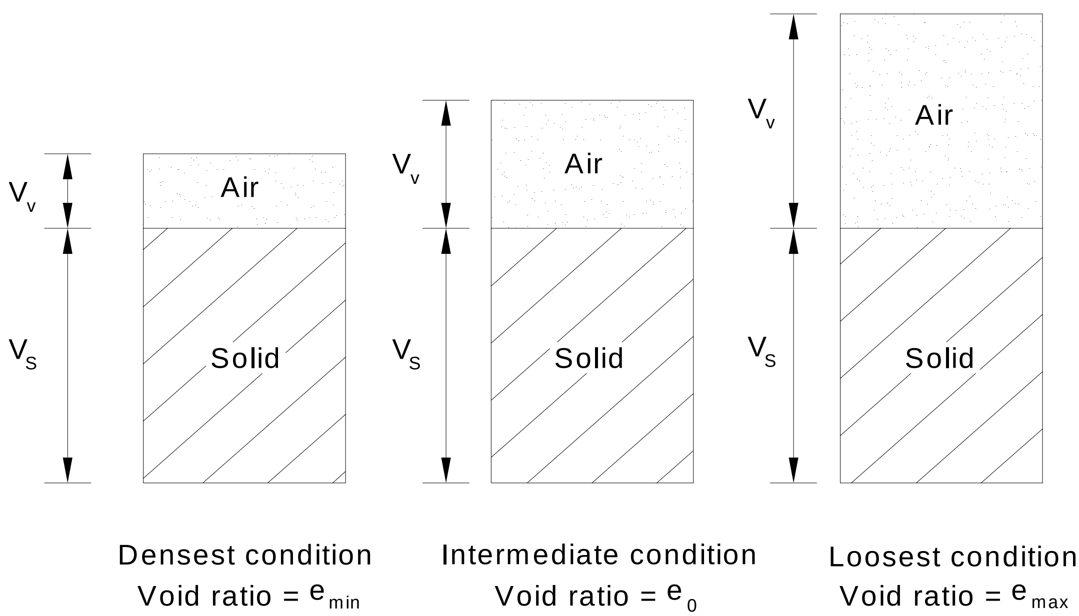


Figure 2.2 Relative conditions of a granular soil (McCarthy, 2007)

From the definitions we have,

$$e = \frac{G_s \gamma_w}{\gamma_d} - 1 \tag{2.2}$$

$$e_{\max} = \frac{G_s \gamma_w}{\gamma_{d_{\min}}} - 1 \tag{2.3}$$

$$e_{\min} = \frac{G_s \gamma_w}{\gamma_{d_{\max}}} - 1 \qquad (2.4)$$

and hence

$$D_r = \frac{\dfrac{1}{\gamma_{d_{\min}}} - \dfrac{1}{\gamma_d}}{\dfrac{1}{\gamma_{d_{\min}}} - \dfrac{1}{\gamma_{d_{\max}}}} = \frac{\gamma_{d_{\max}}(\gamma_d - \gamma_{d_{\min}})}{\gamma_d(\gamma_{d_{\max}} - \gamma_{d_{\min}})} \qquad (2.5)$$

where γ_d = dry unit weight of soil in natural state

$\gamma_{d_{\max}}$ = maximum dry unit weight of the soil corresponding to densest state

$\gamma_{d_{\min}}$ = minimum dry unit weight of the soil corresponding to loosest state

The expression for relative density can also be written in terms of porosity as,

$$D_r = \frac{(\eta_{\max} - \eta)(1 - \eta_{\min})}{(\eta_{\max} - \eta_{\min})(1 - \eta)} \qquad (2.6)$$

where η = porosity of soil in natural state

$\eta_{\max}$ = maximum porosity at loosest state

$\eta_{\min}$ = minimum porosity at densest state

Several investigators have attempted to correlate relative density with the angle of internal friction of soil. Meyerhof (1956) suggested relationship between angle of internal friction (Φ) and relative density.

$\phi^0 = 25 + 0.15D_r$ (Granular soils or sands with more than 5 % silt) (2.7)

$\phi^0 = 30 + 0.15D_r$ (Granular soils or sands with less than 5 % silt) (2.8)

Another term occasionally used in regard to the degree of compaction of coarse-grained soils is relative compaction (R_c) (Das, 2008) which is defined as

$$R_c = \frac{\gamma_d}{\gamma_{d_{max}}} \tag{2.9}$$

R_c in terms of relative density,

$$R_c = \frac{R_0}{1 - D_r(1 - R_0)} \tag{2.10}$$

where R_c and D_r are not in per cent and $R_0 = \dfrac{\gamma_{d_{min}}}{\gamma_{d_{max}}}$

Lee and Singh (1971) reviewed 47 different soils and gave the approximate relation between relative compaction and relative density as follows:

$$R_c = 80 + 0.2D_r \tag{2.11}$$

where R_c and D_r are in per cent

R_c = 80% (minimum) corresponding to D_r =0

D_r =0 represents loosest state

R_c = 100% represents dense state

2.2 THEORY OF COMPACTION

Compaction is the densification of a soil by mechanical means. It is determined by measuring the in-place density of the soil and comparing it to the results of a laboratory compaction test. Soil compaction occurs when soil particles are pressed together, reducing pore space between them. Heavily compacted soils contain few large pores and have a reduced rate of both water infiltration and drainage from the compacted layer. This occurs because large pores are most effective in moving water through the soil when it is saturated. In addition, the exchange of gases slows down in compacted soils, causing an increase in the likelihood of aeration-related problems (Holtz, 1981). Soil compaction changes pore space size, distribution, and soil strength.

One way to quantify the change is by measuring the bulk density. As the pore space is decreased within a soil, the bulk density is increased. Soils with a higher percentage of clay and silt, which naturally have more pore space, have a lower bulk density than sandy soils. For the purpose of defining the physical and index properties of soil, it is more convenient to represent the soil skeleton by a block diagram (Figure 2.3).

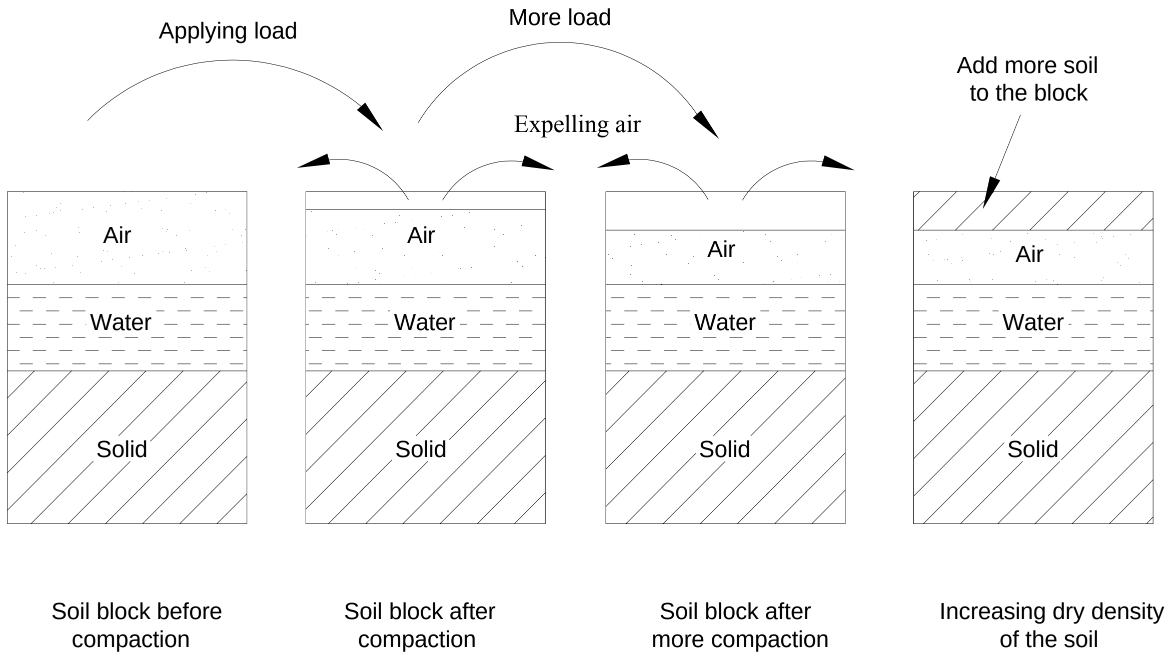


Figure 2.3: Mechanism of Soil Compaction (Johnson and Sallberg, 1960)

2.2.1 Compaction Phenomenon

The compaction process causes the expulsion of air from the soil resulting in a denser material. The theory of compaction and the approach to obtain maximum density has been researched since Proctor first introduced his findings. The compaction process has significant differences for cohesive soil versus cohesionless soils. The major difference is cohesive soils are typically very moisture dependent and cohesionless soils are not. The influence of moisture on compacted density of sand at low water content is less well defined. A scattering of dry density versus water content points is usual at moisture contents below the optimum. The strength gain in sand due to partial saturation and surface tension phenomenon is termed apparent cohesion. Meniscus and surface tension along with the apparent cohesion will disappear when the sand is fully saturated or dries (McCarthy, 2007).

Proctor (1933) recognized that moisture content affects the compaction process. He believed that the cause for a moisture-density curve “breaks over” at optimum moisture content was related to capillarity, frictional forces. He also believed that the force of the compactive effort applied was another factor to overcome the inter-particle friction of the particles. As the water content increased from dry of optimum to wet of optimum, he believed that the water acted as a lubricant between the soil particles. The addition of more water continued to aid the compaction process until the water began replacing the air voids. At this point the compaction process was complete and the addition of more compactive energy would not result in a denser soil.

Lambe (1969) studied the microstructure of clays and developed a theory based on physicochemical properties. He found that compaction of a soil dry of optimum moisture content results in a flocculated soil structure that has high shear strength and permeability. Compaction of a soil wet of optimum moisture content results in a soil with a dispersed soil structure that has low shear strength and permeability. While this information does not directly explain the shape of the compaction curve, it does help explain the strength and volume characteristics of compacted soils.

According to Winterkorn and Fang (1975), the compaction theories based on effective stresses, explain the shape of the compaction curve better than the theories based on lubrication and viscous water. The facts that soils are anisotropic and heterogeneous complicate the research process and add validity to Terzaghi’s remarks about large-scale field tests.

Hilf (1956), as summarized by Winterkorn and Fang (1975), presented another theory about the compaction phenomenon. The theory is based on pore water pressures in unsaturated soils. He developed a curve based on void ratio and water-void ratio. The curve looks similar to a typical moisture-density curve because the minimum void ratio is also the maximum density optimum moisture content point on a moisture density curve. Capillary pressure and pore pressure explain the shape of the curve. The menisci of the water in a drier soil have a high curvature and are stronger than a wetter soil with flatter menisci. The decrease in density after optimum moisture content was attributed to the trapping of air bubbles and a buildup of pore pressure lowering the effectiveness of compaction. The buildup of negative pore pressure in the moisture films surrounding the soil particles were assumed to be interconnected and resulted in an effective compressive stress on the soil skeleton equal to the negative pressure. Subsequent research has shown that capillary pressure may not act as an effective stress in unsaturated soils. An X factor that varies from 0 to 100 with saturation relates how much the capillary pressure acts as an effective stress. This X factor is very difficult to measure and therefore Hilf's theory is still controversial.

Hogentogler, summarized by Hausmann (1990), introduced the next major compaction theory. He also thought that water was a lubricant in the compaction process. He described compaction along the moisture density curve from dry to wet as a four-step process. First, the soil particles become hydrated as water is absorbed. Second, the water begins to act as a lubricant helping to rearrange the soil particles into a denser and denser state until optimum moisture content is reached. Third, the addition of water causes the soil to swell because the soil now has excess water. Finally, the soil approaches saturation as more water is added. His theory was disproven when research showed that the compaction process does not result in complete saturation and compaction wet of optimum moisture content will tend to parallel the zero-air voids curve rather than intersect it.

2.2.2 Field compaction of cohesionless soils

The compaction process may be accomplished by rolling, tamping or vibration. The compaction characteristics are first determined in the laboratory by various compaction tests. The main aim of these tests is to arrive at a standard which may serve as a guide and a basis of comparison for field compaction (Johnson and Sallberg, 1960). Vibratory compaction with smooth drum machines is especially suitable and economical on sand and gravel. High densities can be achieved in few passes with the lift thickness determined by the size of the compactor (D' Appolonia, et al., 1969). Free-draining sand and gravel that contains less than 10% fines are easily compacted, especially when water saturated. When high density is required and the lifts are thick, water should be added. This water will drain out of the lift during the compaction process. If the sand and gravel contains more than 10% fines, the soil is no longer free draining and may become elastic when the water content is high. For this type of soil, there will be optimum moisture content at which maximum density can be reached. Drying of the wet soil may be necessary to reach the optimum moisture content. On poorly graded sand and gravel, it is difficult to achieve high density close to the surface of the fill. There is low shear strength in poorly graded soils and the top layer tends to rise up behind the drum. This is not a problem when multiple lifts are being compacted. The previous top layer will be compacted when the next layer is rolled. However, the difficulty of compacting the surface should be kept in mind when testing for density.

2.3 Previous Work on Laboratory Density Test and Theoretical Analysis

The experimental and analytical studies carried out by various investigators on relative density & compaction behaviour of sand were reviewed and briefly presented in this chapter.

White and Walton (1937) studied on particle packing and particle shape. Relative densities, maximum and minimum void ratio values of sand are greatly affected by particle shapes, sizes and their packing. Spherical particles of equal size theoretically may be packed in five different ways, *e.g.* (1) cubical with a theoretical void space of 47.64%, (2) single-staggered or cubical-tetrahedral with a theoretical void space of 39.55%, (3) double-staggered with a theoretical void space of 30.20%, (4) pyramidal, and (5) tetrahedral; the void spaces in the latter two are identical, 25.95%. Secondary, ternary, quaternary, and quinary spheres each set smaller than its predecessor, may be fitted into the voids in this last type of packing and the voids reduced theoretically to 14.9%. The use of very fine filler in the remaining voids will then reduce the voids theoretically to 3.9%. The use of particles of elliptical shape does not appear to reduce the porosity, but cylindrical-shaped particles, if properly arranged, would reduce the porosity. The practical application of these theoretical methods of packing was studied.

Burmister (1948) offered an analogy regarding limit densities for sands. Limit density values of sands should be regarded as important as such properties as the coefficient of uniformity (C_u), coefficient of curvature (C_c), the mean particle size (D_{50}), and particle shape, among others, when providing a thorough description of sand. Density (or void ratio) limits help to more completely describe the material under consideration and are required when evaluating relative density of in-place soils.

Lee and Suedkamp (1972) studied on the compaction of granular soils and found compaction curve can be irregular if compaction tests are carried out using a larger number of test points and range of moisture contents extending towards zero. Exact form of the curve depends on the type of the material. They found four types of compaction curve such as bell shaped ($30 < w_L < 70$), one & one-half peak ($w_L < 30$), double peak ($w_L < 30$ or $w_L < 70$) and odd shaped ($w_L > 70$).

Selig and Ladd (1973) presented evaluation of relative density measurements and applications. The source and type of errors in relative density are assessed. Based on reported values of maximum, minimum, and density errors, expected errors in relative density are determined. These values may be used as a basis for setting confidence limits on the results of studies involving relative density. Engineering applications of the relative density parameter are discussed, and alternatives to relative density are given. Factors influencing the maximum and minimum densities used in calculating relative density are summarized. Experience in correlating relative density to blow count and strength of cohesionless materials is reviewed. Finally, based on all of the information gathered in the symposium, a series of recommendations are given for modifications to the ASTM test procedures and for needed new procedures.

Townsend (1973) presented comparisons of vibrated density and standard compaction tests on sands with varying amounts of fines. The effects of gradation, percentage and plasticity of fines, and moisture on vibratory and impact compaction of granular soils were investigated by adding measured percentages of low plasticity (ML) and medium plasticity (CL) fines to a poorly graded (SP) and nearly well graded (SW-SP) sand. Results indicated that more fines can be added to uniform sand and that uniform sand densities by vibration more effectively than well graded sand. The same densities are produced by impact and vibratory compaction at higher percentage of fines added to the well graded sand compared to the percent fines added to the uniform sand. Moisture and plasticity are interrelated factors which greatly affect compaction. Saturation facilitated vibratory compaction of low plasticity mixtures; however, for more plastic mixtures, adhesion of the fines to the sand grains restricted vibratory densification. Current compaction test selection criteria, which ignore plasticity and moisture effects by comparing vibratory densities of oven-dry materials with those, determined by standard compaction, can lead to the untenable conclusion that vibratory compaction should be used for sands containing in excess of 20 percent fines.

Holubec and D'Appolonia (1973) studied the effect of particle shape on the engineering properties of granular soils. The use of relative density correlations based on an average sand to predict soil behavior without considering the particle shape can result in poor or misleading predictions. Experimental data indicated that the particle shape has a pronounced effect on all engineering properties. Angularity of the particles increases the maximum void ratio, strength, and deformability of cohesionless soils. Variations in engineering properties due to particle shape can be as large as variations associated with large differences in relative density. Penetration tests in small containers with small rods suggest that the Standard Penetration Test is influenced by both the angularity and density of cohesionless soils.

Youd (1973) studied the factors controlling maximum and minimum densities of sands. Maximum and minimum density tests, conducted on a variety of clean sands, found that the minimum and maximum void-ratio limits are controlled primarily by particle shape, particle size range, and variances in the gradational-curve shape, and that the effect of particle size is negligible. Curves were developed for estimating minimum and maximum void ratios from gradational and particle-shape parameters. Estimates for several natural and commercially graded sands agree well with minimum and maximum void ratios measured in the laboratory. Minimum densities (maximum void ratios) were determined by the standard American Society for Testing and Materials (ASTM), minimum density test method (Test for Relative Density of Cohesionless Soils (D 2049-69)), except that smaller moulds were used. Maximum densities (minimum void ratios) were determined by repeated straining in simple shear, a method which has been shown to give greater densities than standard vibratory methods.

Dickin (1973) studied the influence of grain shape and size upon the limiting porosities of sands. The state of packing of a mass of sand grains is described by its relative porosity which defines the packing relative to maximum and minimum porosities of the material. These limiting porosities depend in turn upon the physical characteristics of the grains themselves. The influence of grain shape and size upon the limiting porosities of quartz sands and glass ballotini was studied. The maximum porosities were determined by deposition of the sample through water as suggested by Kolbuszewski (1948) while minimum porosities were obtained by vibration under water. Shape parameters for the sands were determined from a correlation between the time of flow of a 0.5-kg specimen and the sphericity measured by examination of individual grains. Both maximum and minimum porosities decreased with increasing sphericity while tests on glass ballotini indicated that the effect of grain size was negligible. The porosity interval was approximately 12.5 percent for all the sands and 11 percent for spherical ballotini. Mixtures of sand and ballotini gave reasonable agreement with the trend shown by the separate materials.

Johnston (1973) presented laboratory studies of maximum and minimum dry densities of cohesionless soils. Some of the differences in results of tests for the maximum and minimum dry densities of cohesionless soils were examined. He investigated the reproducibility of results of maximum and minimum densities for two types of sands by a comparative test program and suggested an empirical correlation for the uniformity coefficient versus maximum and minimum densities. He gave comparison between the Providence Vibrated Density method and the vibratory table method. The results shown that one of the important variables in determining the maximum density of cohesionless soils using the vibratory table method was the amplitude of the vibrating mould.

Walter et al. (1982) determined the maximum void ratio of uniform cohesionless soils. A testing program was conducted to evaluate several methods of determining the maximum void ratio of cohesionless soils. Preliminary test results indicated that a new procedure called the tube method was consistent in attaining reliable maximum void ratios. In performing the tube method, a long narrow tube or cylinder opened at both ends was placed upright in a mold of known volume. A quantity of dry sand sufficient to fill the mold was placed in the tube and then the tube was slowly extracted to allow sand to trickle into the mold until the mold overflows. The sand was then screeded level with the top of the mould and the void ratio was calculated from measured masses and volumes and the specific gravity of the sand. To evaluate various methods of determining maximum void ratios, a test series was carried out by using eight different test procedures on four sands. Statistical analyses of the data indicated that the tube method yielded higher values of maximum void ratio than did the other procedures. In addition, a testing program involving nine inexperienced operators demonstrated that by using the tube method an individual operator was able to reproduce results consistently and the operators were able to replicate one another's results well within limits mandated by practical applications.

Aberg (1992) presented void ratio of non cohesive soils and similar materials. A new approach was presented to the topic of numerical description of void characteristics of noncohesive soils and similar granular materials. Based upon a simple stochastic model of the void structure and void sizes, theoretical equations were derived by means of which the void ratio of a soil can be calculated from its grain-size distribution. The calculations also give information about type of grain structure and the grain size that separates fixed grains and possible loose grains were determined. The equations also considered the grain shape, degree of densification, and size of compaction container. Results of numerous laboratory compaction tests on uniform to broadly graded sand, gravel, and crushed-rock materials confirm the general forms of the derived equations, were the basis for evaluation of certain parameters.

Aberg (1996) investigated grain-size distribution for smallest possible void ratio. The theoretical equations for void ratio as a function of grain size distribution were used to find the grain size distribution that give the smallest possible void ratio for highly densified, cohesion less soils and similar materials. Both numerical and analytical methods were used. He also studied the void sizes in granular soils. The stochastic model was used to find the distribution of void volume as a function of void size (void-chord length).

Lade et al. (1998) studied the effects of non-plastic fines on minimum and maximum void ratios of sand. The behavior of sand was affected by the content of non-plastic fine particles. They have studied the effect of degree of fines content on the minimum and maximum void ratios. A review was presented of previous theoretical and experimental studies of minimum and maximum void ratios of single spherical grains, packings of spheres of several discrete sizes, as well as optimum grain-size ratios to produce maximum densities. A systematic experimental study was performed on the variation of minimum and maximum void ratios to signify the contents of fines for sands with smoothly varying particle size curves and a large variety of size distributions. It was shown that the fines content plays an important role in determining the sand structure and the consequent minimum and maximum void ratios.

Masih (2000) developed a mathematical formula to get desired soil density. He used statistical parameters of the soil grains distribution to predict the soil maximum dry density and then applied the fine biasness coefficient to predict the new density of the soil after mixing any amount of fine particles with the original soil. Lab testing results were compared with the results of the prediction. They were found to be in total agreement, and the margin of error was found to be quite low.

Barton et al. (2001) measured the effect of mixed grading on the maximum dry density of sands. During cut and fill operations, compaction using sands from different sources may be carried out. The resulting mixed sand will have different compaction characteristics than those of the parent sands. An increase in dry density will result as the grading moves towards more ideal characteristics for dense packing. Laboratory compaction tests using pluviation and the vibrating hammer method have been carried out to measure this increase in dry density. The resulting value was generally significantly greater than the result predicted by taking the mean value of dry density given by the parent sands.

Cubrinovski and Ishihara (2002) studied the maximum and minimum void ratios characteristics of sands. Characteristics of the maximum and minimum void ratios of sands and their possible use for material characterization have been investigated in this study. Data of over 300 natural sandy soils including clean sands, sands with fines and sands containing small amount of clay-size particles have been used to examine the influence of fines, grain-size composition and particle shape on e_{max}, e_{min} and void ratio range (e_{max} - e_{min}). A set of empirical correlations were presented which clearly demonstrate the link between these void ratios and material properties of sands. The key advantage of (e_{max} - e_{min}) over conventional material parameters such as F_c and D_{50} is that (e_{max} - e_{min}) was indicative of the overall grain-size composition and particle characteristics of a given sand and found the combined influence of relevant material factors. The void ratio range indicated a general basis for comparative evaluation of material properties over the entire range of cohesionless soils. Three distinct linear correlations were found to exist between e_{max} and e_{min} for clean sands, sands with 5-15% fines and sands with 15-30% fines respectively, thus illustrated that the standard JGS procedures for minimum and maximum densities of sands can provide reasonably consistent e_{max} and e_{min} values for sands with fines content of up to 30%.

Omar et al. (2003) investigated the compaction characteristics of granular soils in United Arab Emirates. A study was undertaken to assess the compaction characteristics of such soils and to develop the governing predictive equations. For the purposes of this study, 311 soil samples were collected from various locations in the United Arab Emirates and tested for various including grain-size distribution, liquid limit, plasticity index, specific gravity of soil solids, maximum dry density of compaction, and optimum moisture content following ASTM D 1557-91 standard procedure C. A new set of 43 soil samples were collected and their compaction results were used to test the validity of predictive model. The range of variables for these soils were as follows: percent retained on US sieve #4 (R#4): 0–68; Percent passing US sieve #200 (P#200): 1–26; Liquid limit: 0–56; Plasticity index: 0–28; Specific gravity of soil solids: 2.55–2.8. Based on the compaction tests results, multiple regression analyses were conducted to develop mathematical models and nomographic solutions to predict the compaction properties of soils. The results indicated that the nomographs could predict well the maximum dry density within ±5% confidence interval and the optimum moisture content within ±3%.

Itabashi et al. (2003) studied the grain shape and packing property of unified coarse granular materials. Particle shape analysis and random packing experiences were carried out used by unified stainless ball and five natural granular materials which were produced under different natural environments. They found that three particle shape parameters (form unevenness FU, order number Mi and fractal dimension FD) of six granular materials much differ from each other, and these were able to evaluate the difference of ultimate porosity.

Hatanaka and Feng (2006) estimated relative density of sandy soils from SPT-N value. The applicability of three previous empirical correlations proposed for estimating relative density of sandy soils based on the SPT *N*-value, effective overburden stress and soil gradation characteristics was investigated using a data base of relative density obtained from high quality undisturbed samples of fine to medium sand with $F_c \leq$ 20%, $D_{50} \leq$ 1.0 mm and $D_{max} \leq$ 4.75 mm. All undisturbed samples were recovered by in-situ freezing method. The relative density estimated by Meyerhof's method (1957) was in the range of ＋15%～－45% of the measured values. Meyerhof's method (1957) was modified by Tokimatsu and Yoshimi (1983) by considering the effect of fines content on the SPT *N*-value. The relative density estimated by Tokimatsu and Yoshimi's method (1983) was in the range of ＋25%～－20% of the measured values. The underestimation of relative density of Meyerhof's method (1957) was modified. On the contrary, the overestimation of relative density was more significant than Meyerhof's method. The relative density estimated by the method proposed by Kokusho et al. (1983) was in the range of ＋20% to －35% of the measured values even for dense sand with a relative density larger than 60%. Meyerhof's method (1957) and the method proposed by Kokusho et al. (1983) have a common disadvantage that they will extremely underestimate the relative density of fine to medium sand for SPT *N*-value lower than about 8. A simple empirical correlation was proposed to estimate the relative density of fine to medium sand based on the normalized SPT *N*-value, N_1. The relative density estimated by the proposed method was in the range of ＋ 15% to －30% of the measured values for N_1 in the range between 0 and 50. As a whole, the proposed method was less in errors for estimating relative density compared with those estimated by Meyerhof's method (1957) and the method proposed by Kokusho et al. (1983). Based on a data base of undisturbed samples with data of fines content obtained from the SPT spoon samples, the method proposed was again compared with the three previous methods. The relative density estimated by the proposed method based on the above data base is in the range of ＋15% to －10% of the measured values. Among four methods, as a whole, the proposed method found to be the least errors in estimation of relative density. The proposed method was also modified by taking into account of the effect of fines content of SPT samples. The relative density estimated by the modified method based on the fines content is almost in the range of ＋10% to － 10% of the measured values. Two empirical correlations proposed were less in errors of estimating relative density compared with three previous methods. The range of relative density estimated was consistent with the range of the measured values (40% to 90%). The empirical correlations proposed in the study should be applied to fine to medium sand with $F_c \leq$ 20%, $D_{50} \leq$ 1.0 mm and $D_{max} \leq$ 4.75 mm.

Cho et al. (2006) studied the particle shape effects on packing density, stiffness and strength for natural and crushed sands. The experimental data and results from published studies were gathered into two databases to explore the effects of particle shape on packing density and on the small-to-large strain mechanical properties of sandy soils. In agreement with previous studies, these data confirmed that increase in angularity or eccentricity produces an increase in e_{max} and e_{min}. Therefore, particle shape emerged as a significant soil index property that needs to be properly characterized and documented, particularly in clean sands and gravels.

Muszynski (2006) determined the maximum and minimum densities of poorly graded sands using a simplified method. The simplified method was easy to perform, requires less sample volume, and was faster than the conventional methods for determining these properties. Results of this study indicated that the simplified method gives limit density values comparable to those obtained using conventional methods for clean poorly graded fine to medium sands. Limitations of the simplified method were also discussed.

Sinha and Wang (2008) developed Artificial Neural Network (ANN) prediction models for soil compaction and permeability. The ANN prediction models were developed from the results of classification, compaction and permeability tests, and statistical analyses. The test soils were prepared from four soil components, namely, bentonite, limestone dust, sand and gravel. These four components were blended in different proportions to form 55 different mixes. The standard Proctor compaction tests were adopted, and both the falling and constant head test methods were used in the permeability tests. The permeability, MDD and optimum moisture content (OMC) data were trained with the soil's classification properties by using an available ANN software package. Three sets of ANN prediction models were developed, one each for the MDD, OMC and permeability (PMC). A combined ANN model was also developed to predict the values of MDD, OMC, and PMC. A comparison with the test data indicate that predictions within 95% confidence interval can be obtained from the ANN models developed.

Abdel-Rahman (2008) predicted the compaction of cohesionless soils using ANN. An artificial neural network (ANN) model was developed to predict the two main compaction parameters: the maximum dry unit weight $(\gamma_d)_{max}$ and the optimum moisture content (w_{omc}). The study was performed based on the results of modified Proctor tests (ASTM D 1557). Based on the ANN model, empirical equations were developed to predict the compaction characteristics of graded cohesionless soils. The predicted values using the ANN model and the empirical equations were compared with a set of laboratory measurements. A parametric study on the developed equations was performed to present the control parameters that set the values of $(\gamma_d)_{max}$ and w_{omc}.

Gunaydın (2008) estimated the soil compaction parameters by using statistical analyses and artificial neural networks. The data collected from the dams in some areas of Nigde (Turkey) were used for the estimation of soil compaction parameters. Regression analysis and artificial neural network estimation indicated strong correlations (r^2 = 0.70–0.95) between the compaction parameters and soil classification properties. It has been shown that the correlation equations obtained as a result of regression analyses are in satisfactory agreement with the test results.

2.4 MOTIVATION & OBJECTIVE OF PRESENT RESEARCH WORK

From the review of literature available, it is seen that enough work has been done on the void ratio, angularity, grain shape, grain size and their packing arrangements of various types of soil. Various testing methods for determining minimum and maximum voids ratio of sand, ANN models and nomographs for predicting maximum dry density (MDD), optimum moisture content (OMC) of soil have been presented by some investigators. However, accurate determination of compaction parameters such as MDD and OMC of sand is difficult. In most specifications for earthwork, the contractor is instructed to achieve a compacted field dry unit weight of 95 to 98% of the maximum dry unit weight determined in the laboratory by either the standard or modified Proctor test. For the compaction of granular soils, specifications are sometimes written in terms of the required relative density. Empirical correlations have been made by earlier investigators in predicting relative density of sandy soils from SPT test data in the field. It is reported in literature that the maximum and minimum voids ratio decrease with increase in the mean grain size (D_{50}). Minimum and maximum voids ratios range ($e_{max} – e_{min}$) of sandy soils or soils with low fine contents is a function of mean grain size (D_{50}). From the available literature, it is learnt that the correlation of relative density of granular soils have not been attempted in the laboratory with the index property like grain size. Therefore, a relationship can be established in the laboratory with e_{max}, e_{min} and mean grain size. Similarly the relative density at particular compactive effort can be correlated with mean grain size of the granular soils.

The main objectives of present research work are as follows:

- Characterization of relative density of sand by establishing relationship between void ratios with mean grain size (D_{50}) with reference to different compaction energy.
- Prediction of maximum and minimum void ratio (e_{max}, e_{min}) from D_{50}.
- Prediction of void ratios (e) from D_{50} corresponding particular energy level of compaction
- Prediction of Relative density of sand at the particular compaction energy level.

CHAPTER 3

EXPERIMENTAL PROGRAMME

The properties of soil which are indicative of the engineering properties are called index properties. The tests which are required to determine the index properties are known as classification tests. The soils are classified and identified based on the index properties. The main index properties of sand are particle size and relative density.

3.1 TEST SPECIMENS

Natural sand samples were collected from 10 rivers of Orissa (Mahanadi, Kathojodi, Rushikulya, Bramhni, Baitarani, Subarnarekha, Budhabalanga, Salandi, Daya, Koel). Total 55 samples were used for the experimentation. Various tests such as specific gravity (G), grain size distribution (D_{60}, D_{50}. D_{30}, D_{10}, C_u, C_c), and relative density (e_{max}, e_{min}, e) were conducted for determination of basic physical properties.

3.2 TEST METHODOLOGY

3.2.1 Determination of specific gravity (*G*)

Specific gravity (G) of solid particles is the ratio of the mass of a given volume of solids to the mass of an equal volume of gas-free distilled water at 4^0 C temperatures.

$$G = \frac{\gamma_s}{\gamma_w} \tag{3.1}$$

where γ_s = unit weight of solid

γ_w = unit weight of water

The specific gravity of sand was determined in laboratory using a density bottle (as per IS: 2720 – Part III, 1980). The bottle of 250 ml capacity was cleaned and dried at a temperature of 105^0 C to 110^0 C and cooled. The weight of the bottle was taken. About 50 gm of oven dry sample of sand was taken in the bottle and weighed. Distilled water was then added to cover the sample and the sand was allowed to soak water for 30 minutes. Air entrapped in the sand was expelled by gentle heating. More water was added to the bottle up to a mark and weighed. Then the bottle was emptied, washed and refilled with distilled water up to that previous mark and weighed. The specific gravity of sand was determined by the equation,

$$G=\frac{M_2-M_1}{(M_2-M_1)-(M_3-M_4)} \tag{3.2}$$

where M_1 = mass of the empty bottle

M_2 = mass of the empty bottle and dry sand

M_3 = mass of the empty bottle, sand and water

M_4 = mass of the bottle filled with water

3.2.2 Determination of grain size distribution

Particle size analysis or sieve analysis is a method of separation of sands into different fraction based on the particle size. It expresses quantitatively the proportions, by mass of various sizes of particles present in the sand. It is shown graphically on a particle size distribution curve. Oven dry sand samples of 1000 gm were taken for sieve analysis. Sieves of size 4.75 mm, 2 mm, 1 mm, 600μ, 425μ, 300μ, 212μ, 150μ and75μ were used for sieving (as per IS: 2720 – Part IV, 1985). All samples were passed through 4.75 mm sieve and very little fines (< 5 %) were retained in pan through 75μ sieve. Hence all samples were considered to be clean sands having very little fines and no gravel fractions. By taking the weights of sand fraction retained on various sieves, particle size distribution curve was plotted. The percentage finer (*N*) than a given size has been plotted as ordinate (on natural scale) and the corresponding particle size as abscissa (on log scale). The particle size distribution curve, also known as gradation curve represents the distribution of particle of different sizes in the sand mass. The particle size distribution curve also reveals whether the sand is well graded (particle of different sizes in good proportion) or poorly graded (particle almost of same sizes). From this curve, mean grain size (D_{50}), coefficient of uniformity (C_u), and coefficient of curvature (C_c) were determined.

Mean grain size (D_{50}) is the particle size corresponding to 50 % finer, which means 50 % of the sand is finer than this size.

The uniformity of sand is expressed qualitatively by the term uniformity coefficient (C_u),

$$C_u = \frac{D_{60}}{D_{10}} \tag{3.3}$$

where D_{60} = particle size such that 60 % of the sand is finer than this size

D_{10} = effective size

= particle size such that 10 % of the sand is finer than this size

The larger the numerical value of C_u, the more is the range of particles. Sands with a value of C_u less than 6 are poorly graded sand and value of C_u 6 or more, are well graded.

The general shape of particle size distribution curve is described by another coefficient known as the coefficient of curvature (C_c) or the coefficient of gradation (C_g),

$$C_c = \frac{D_{30}{}^2}{D_{60} \times D_{10}} \tag{3.4}$$

where D_{30} = particle size corresponding to 30 % finer

D_{60} = particle size corresponding to 60 % finer

D_{10} = particle size corresponding to 10 % finer

For well graded sand, the value of C_c lies between 1 and 3 and for poorly graded sand the C_c value is less than 1.

3.2.3 Determination of maximum void ratio (e_{max})

For determination of minimum dry density (maximum void ratio) of sand, oven dry sample of sand was taken. The minimum dry density was found by pouring the dry sand in a mould using a pouring device (as per IS: 2720 – Part XIV, 1983) and the spout of the pouring device was so adjusted that the height of free fall was always 25 mm. A mould of volume 3000 cm^3 was used for the purpose. The weight and the volume of the sand deposited were found and the dry density of the soil was determined as under,

$$\gamma_{d_{\min}} = \frac{W_{\min}}{V} \tag{3.5}$$

where $W_{\min}$ = weight of dry sand in the mould

V = volume of the mould

Then maximum void ratio can be determined by using the equation,

$$e_{\max} = \left(\frac{G\gamma_w}{\gamma_{d_{\min}}} \right) - 1 \tag{3.6}$$

where G = specific gravity of sand

γ_w = unit weight of water

$\gamma_{d_{\min}}$ = minimum dry unit weight of sand

3.2.4 Determination of minimum void ratio ($e_{\min}$)

The maximum dry density (minimum void ratio) was determined either by the dry method or the wet method (as per IS: 2720 – Part XIV, 1983). In the dry method the mould was filled thoroughly with mixed oven dry sand. A surcharge load was placed on the soil surface and the mould was fixed to a vibrating table. The specimen was vibrated for 8 minutes. The weight of the dry sand in the compacted state was found. The maximum dry density was given by

$$\gamma_{d_{\max}} = \frac{W_{\max}}{V} \tag{3.7}$$

where $W_{\max}$ = weight of dry soil

V = volume of the mould

Then minimum void ratio can be determined by using the equation,

$$e_{\min} = \left(\frac{G\gamma_w}{\gamma_{d_{\max}}} \right) - 1 \tag{3.8}$$

where G = specific gravity of sand

γ_w = unit weight of water

$\gamma_{d_{\max}}$ = maximum dry unit weight of sand

The maximum dry density of sand was also determined in the saturated state. In this method, the mould was filled with wet sand and water is added till a small quantity of free water accumulates on the free surface of the sand. During and just after filling the mould, vibration was done for a total of 6 minutes. Water appearing on the surface of sand was removed. A surcharge mass is placed on the sand and the mould was vibrated again for 8 minutes. The weight (W_{max}) of the sand was determined after oven drying the sample. A mould volume of 3000 $cm^3$was used for both dry and wet method. For achieving the maximum dry density of sand out of 55 samples, some samples were tested by above two methods i.e. dry method and wet method. However, the results indicated that tests on dry condition gave maximum dry density. Therefore, the dry method has been adopted for all the samples to get the minimum void ratio.

3.2.5 Determination of void ratio corresponding to maximum dry density (MDD)

Standard and modified Proctor compaction tests were used in the laboratory to determine the maximum dry unit weight $\{\gamma_{d(\mathrm{max-lab})}\}$ of soils to be used in the field. In most specification for earth works, the contractor is instructed to achieve a compacted field dry unit weight of 95 to 98 % of the maximum dry unit weight determined in the laboratory by either the standard or modified Proctor test (Arora, 2005). The maximum dry unit weight of compaction is used for end-product specifications in terms of relative compaction (R) for construction work. Relative compaction is defined as

$$R_c\ (\%) = \frac{\gamma_{d(\mathrm{field})}}{\gamma_{d(\mathrm{max-lab})}} \times 100 \tag{3.9}$$

where $\gamma_{d(\mathrm{field})}$ is the desired unit weight of compaction in the field.

For the compaction of granular soils, specifications are sometimes written in terms of the required relative density (D_r) (Das, 2006). Holtz and Kovacs (1981) suggested that, for granular soils with less than 12% fines (i.e., passing 0.075-mm sieve), relative density (D_r) may be a better indicator for end-product compaction specifications than relative compaction. Relative density (D_r) is defined as,

$$D_r = \frac{\gamma_{d_{\max}} \,(\gamma_{d_{field}} - \gamma_{d_{\min}})}{\gamma_{d_{field}} \,(\gamma_{d_{\max}} - \gamma_{d_{\min}})} \tag{3.10}$$

Relative density (D_r) in terms of void ratio,

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \times 100 \tag{3.11}$$

where $e_{\max}$, $e_{\min}$ = maximum and minimum void ratios of the granular soil respectively

e = void ratio of the compacted soil.

The void ratios (e) obtained from the maximum dry unit weights of compaction for each type of test (and, hence, compaction energy) were used to obtain the relative density of compaction. The purpose of laboratory compaction testing is to find out how the sand may respond when compacted on site. So the laboratory method, which best replicates the field compaction equipment that is to be used on an earthworks job. Compaction tests at various energy levels such as: Standard Proctor test, Modified Proctor test, Reduced Standard Proctor test, and Reduced Modified Proctor tests have been conducted in the laboratory for the present work. Table 3.1 gives the energy requirement for the above four tests conducted in the laboratory. The energy level corresponding to these tests were determined as follows:

$$\mathrm{E} = \left(\frac{\text{No. of blows per layer} \times \text{No. of layers} \times \text{Wt. of hammer} \times \text{Ht. of drop of hammer}}{\text{Volume of mould}} \right) \tag{3.12}$$

Table 3.1 Compaction energy for different proctor compaction tests

Test Type	**No. of blows per Layer**	**No .of layers**	**Wt. of hammer (kg)**	**Ht. of drop of hammer (m)**	**Volume of mould (cm^3)**	**Energy $kN\text{-}m/m^3$**
Reduced Standard Proctor	15	3	2.6	0.31	1000	355.80 ≅356
Standard Proctor	25	3	2.6	0.31	1000	593.01 ≅593
Reduced Modified Proctor	12	5	4.89	0.45	1000	1295.21 ≅1295
Modified Proctor	25	5	4.89	0.45	1000	2698.36 ≅2698

All the four tests as mentioned above are discussed below briefly.

Standard Proctor Compaction Test**:** (as per IS: 2720 – Part VII, 1980)

Sand was compacted into a mould in 3 equal layers, each layer receiving 25 numbers of blows of a hammer weight 2.6 kg. The height of drop of hammer was 0.31m.The energy (compactive effort) supplied in this test was 593 kN-m/m^3.

Modified Proctor Compaction Test: (as per IS: 2720 – Part VIII, 1983)

Sand was compacted into a mould in 5 equal layers, each layer receiving 25 numbers of blows. To provide the increased compactive effort (energy supplied = 2698 kN-m/m^3) a heavier hammer 4.89 kg and a greater drop 0.45m height for the hammer were used.

Reduced Standard Proctor Compaction Test:

The procedure and equipment is essentially the same as that used for the Standard Proctor test. However, each layer received 15 numbers of blows of a hammer/per each layer. The energy (compactive effort) supplied in this test is 356 kN-m/m^3.

Reduced Modified Proctor Compaction Test:

The procedure and equipment is essentially the same as that used for the Modified Proctor test. Each layer of sand received 12 numbers of blows of a hammer/per each layer. The energy (compactive effort) supplied in this test is 1295 kN-m/m^3.

For determination of void ratio of sand corresponding to different energy levels an indirect method was used. In this method corresponding to each energy level, maximum dry density (MDD) was obtained from the compaction curve.

Then void ratio corresponding to that MDD was calculated by the following equation.

$$e = \left(\frac{G\gamma_w}{\gamma_d}\right) - 1 \qquad (3.13)$$

where G = specific gravity of sand

γ_w = unit weight of water

γ_d = dry unit weight of sand corresponding to different energy levels in Proctor test

3.2.6 Determination of relative density (D_r)

The relative density can be determined by the relation,

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \times 100 \tag{3.14}$$

where

e = voids ratio calculated from laboratory proctor test,

e_{max} = maximum voids ratio calculated from laboratory test

e_{min} = minimum voids ratio calculated from laboratory test

The values of, e_{max}, e_{min}, e are mentioned as earlier in equations 3.6, 3.8 and 3.13 respectively.

The relative density corresponding to standard Proctor test, $(D_r)_s$

$$(D_r)_s = \frac{e_{\max} - e_s}{e_{\max} - e_{\min}} \times 100 \tag{3.15}$$

where e_s = voids ratio calculated from MDD of standard Proctor test

The relative density corresponding to modified Proctor test, $(D_r)_m$

$$(D_r)_m = \frac{e_{\max} - e_m}{e_{\max} - e_{\min}} \times 100 \tag{3.16}$$

where e_m = voids ratio calculated from MDD of modified Proctor test

The relative density corresponding to reduced standard Proctor test, $(D_r)_{rs}$

$$(D_r)_{rs} = \frac{e_{\max} - e_{rs}}{e_{\max} - e_{\min}} \times 100 \tag{3.17}$$

where e_{rs} = voids ratio calculated from MDD of reduced standard Proctor test

The relative density corresponding to reduced modified Proctor test, $(D_r)_{rm}$

$$(D_r)_{rm} = \frac{e_{\max} - e_{rm}}{e_{\max} - e_{\min}} \times 100 \tag{3.18}$$

where e_{rm} = voids ratio calculated from MDD of reduced modified Proctor test

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INDEX PROPERTY OF SAND

The relative density (D_r) is an important index property of sand. Fifty five numbers of clean sand samples have been tested in the laboratory for predicting the relative density from grain size analysis. The mean grain size of the sand particle (D_{50}) is another important index property. Effort has been made to correlate the relative density with the grain size of the sand particles. It is observed that out of many properties, mean grain size of sand plays an important role in predicting the relative density and thus the compaction control of sand. In this chapter every effort has been put to correlate the relative density at various energy levels with the mean grain size. The grain size analysis of 55 samples has been obtained. Figure 4.1 shows the range of grain size distribution of the samples tested in the laboratory. The values of specific gravity (G), mean grain size (D_{50}), coefficient of uniformity (C_u), coefficient of curvature (C_c), maximum void ratio (e_{max}), and minimum void ratio (e_{min}) were determined in the laboratory and shown in Table 4.1.

Table 4.1 Index properties of sand samples tested

Sample No.	G	D_{50}	D_{60}	D_{30}	D_{10}	C_u	C_c	e_{max}	e_{min}
1	2.627	0.7	0.8	0.49	0.35	2.29	0.86	0.791	0.504
2	2.726	0.35	0.36	0.32	0.25	1.44	1.14	0.949	0.662
3	2.655	0.58	0.68	0.41	0.32	2.13	0.77	0.775	0.512
4	2.705	0.35	0.36	0.31	0.23	1.57	1.16	0.967	0.678
5	2.717	0.55	0.68	0.405	0.325	2.09	0.74	0.771	0.51
6	2.697	0.41	0.46	0.36	0.3	1.53	0.94	0.868	0.563
7	2.764	0.375	0.4	0.33	0.26	1.54	1.05	0.888	0.597
8	2.729	0.365	0.39	0.33	0.27	1.44	1.03	0.906	0.619
9	2.634	0.54	0.6	0.42	0.33	1.82	0.89	0.89	0.577
10	2.726	0.75	0.85	0.57	0.6	1.42	0.64	0.703	0.389
11	2.649	0.35	0.38	0.3	0.185	2.05	1.28	0.766	0.484
12	2.652	0.58	0.64	0.415	0.33	1.94	0.82	0.841	0.555
13	2.702	0.36	0.39	0.3	0.22	1.77	1.05	0.844	0.552
14	2.693	0.35	0.38	0.3	0.23	1.65	1.03	0.827	0.577
15	2.711	0.38	0.4	0.32	0.24	1.67	1.07	0.803	0.544
16	2.696	0.35	0.4	0.28	0.23	1.74	0.85	0.801	0.544
17	2.688	0.6	0.7	0.4	0.31	2.26	0.74	0.732	0.483

Sample No.	G	D_{50}	D_{60}	D_{30}	D_{10}	C_u	C_c	e_{max}	e_{min}
18	2.684	0.38	0.41	0.32	0.2	2.05	1.25	0.761	0.516
19	2.668	0.35	0.37	0.31	0.23	1.61	1.13	0.842	0.569
20	2.679	0.35	0.36	0.3	0.2	1.80	1.25	0.853	0.566
21	2.7	0.34	0.37	0.3	0.2	1.85	1.22	0.919	0.633
22	2.707	0.34	0.37	0.3	0.23	1.61	1.06	0.919	0.625
23	2.656	0.36	0.38	0.32	0.23	1.65	1.17	0.857	0.562
24	2.68	0.35	0.37	0.3	0.235	1.57	1.04	0.861	0.567
25	2.663	0.36	0.39	0.3	0.22	1.77	1.05	0.729	0.457
26	2.662	0.39	0.45	0.33	0.24	1.88	1.01	0.71	0.468
27	2.692	0.36	0.4	0.29	0.23	1.74	0.91	0.757	0.512
28	2.697	0.35	0.39	0.29	0.19	2.05	1.13	0.843	0.542
29	2.587	2.4	2.8	1.6	0.38	7.37	2.41	0.509	0.235
30	2.59	1.1	1.8	0.43	0.27	6.67	0.38	0.505	0.273
31	2.589	2.6	3	1.9	0.45	6.67	2.67	0.482	0.229
32	2.586	1.95	2.4	0.71	0.33	7.27	0.64	0.481	0.243
33	2.584	2.4	2.8	1.6	0.38	7.37	2.41	0.544	0.256
34	2.592	1.6	2	0.6	0.27	7.41	0.67	0.492	0.233
35	2.589	1.7	2.2	0.73	0.3	7.33	0.81	0.487	0.249
36	2.584	1.4	2.1	0.38	0.26	8.08	0.26	0.48	0.268
37	2.578	2.4	2.85	0.98	0.29	9.83	1.16	0.47	0.225
38	2.575	0.49	0.9	0.36	0.275	3.27	0.52	0.578	0.356
39	2.581	1	1.25	0.43	0.275	4.55	0.54	0.583	0.278
40	2.576	0.78	1.2	0.38	0.27	4.44	0.45	0.545	0.315
41	2.581	1	1.25	0.51	0.295	4.24	0.71	0.596	0.303
42	2.556	0.8	1.1	0.465	0.28	3.93	0.70	0.574	0.308
43	2.59	0.93	1.25	0.485	0.275	4.55	0.68	0.579	0.301
44	2.574	1.25	1.45	0.7	0.33	4.39	1.02	0.563	0.297
45	2.607	1.4	1.7	0.78	0.35	4.86	1.02	0.548	0.292
46	2.601	0.41	0.72	0.32	0.24	3.00	0.59	0.551	0.346
47	2.617	1.15	2	0.365	0.26	7.69	0.26	0.498	0.297
48	2.557	1.25	1.5	0.425	0.27	5.56	0.45	0.492	0.261
49	2.566	1.2	1.4	0.72	0.32	4.38	1.16	0.59	0.302
50	2.574	1.1	1.3	0.42	0.26	5.00	0.52	0.524	0.288
51	2.537	1.3	1.5	0.97	0.41	3.66	1.53	0.621	0.331
52	2.535	1.3	1.5	1	0.395	3.80	1.69	0.621	0.335
53	2.554	1.25	1.4	0.84	0.35	4.00	1.44	0.618	0.341
54	2.564	1.1	1.25	0.61	0.285	4.39	1.04	0.607	0.33
55	2.556	1.25	1.45	0.76	0.31	4.68	1.28	0.571	0.284

From the above table, it is seen that D_{50} values have wide range varying from 0.34 to 2.6. Since out of total 55 samples, 10 numbers of samples have C_u values greater than 6 and the rest having C_u values less than 6. Thus as per the IS classification, the ten samples are classified as well graded and the rest to be poorly graded sand.

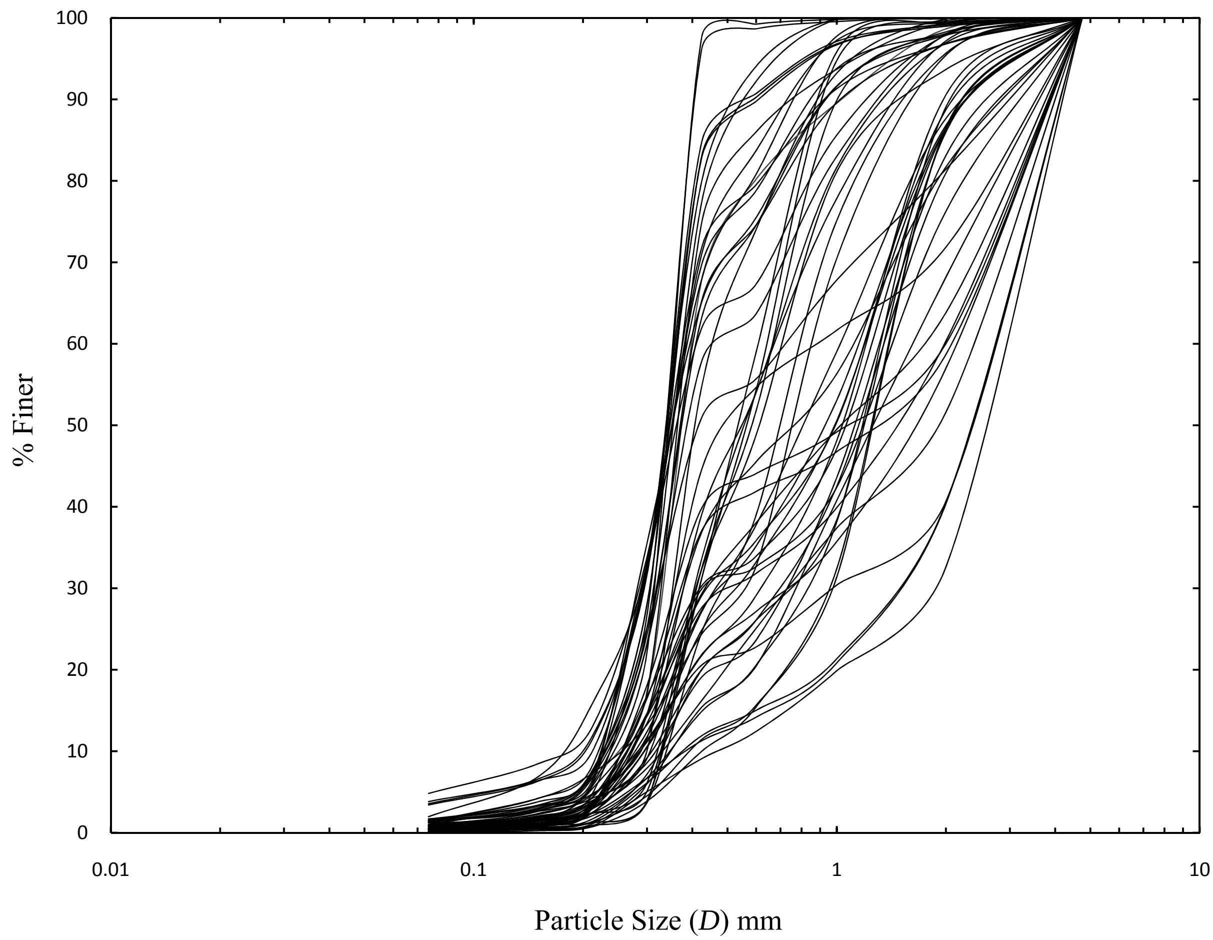


Figure 4.1: Range of grain-size distribution for sand samples tested

4.1.1 Prediction of maximum void ratio (e_{max}) from mean grain size (D_{50})

The voids ratio in the loosest state (e_{max}) of 55 samples has been plotted against their corresponding mean grain size (D_{50}). Several equations have been tried to fit to these experimental data. However, the best fit line to these sets of data is shown in Figure 4.2.

$$e_{max} = 0.6042\ D_{50}^{-0.304} \tag{4.1}$$

$$r^2 = 0.76$$

The least square value is comparatively good than other set of equations. For the sake of space and brevity other equations are not shown here.

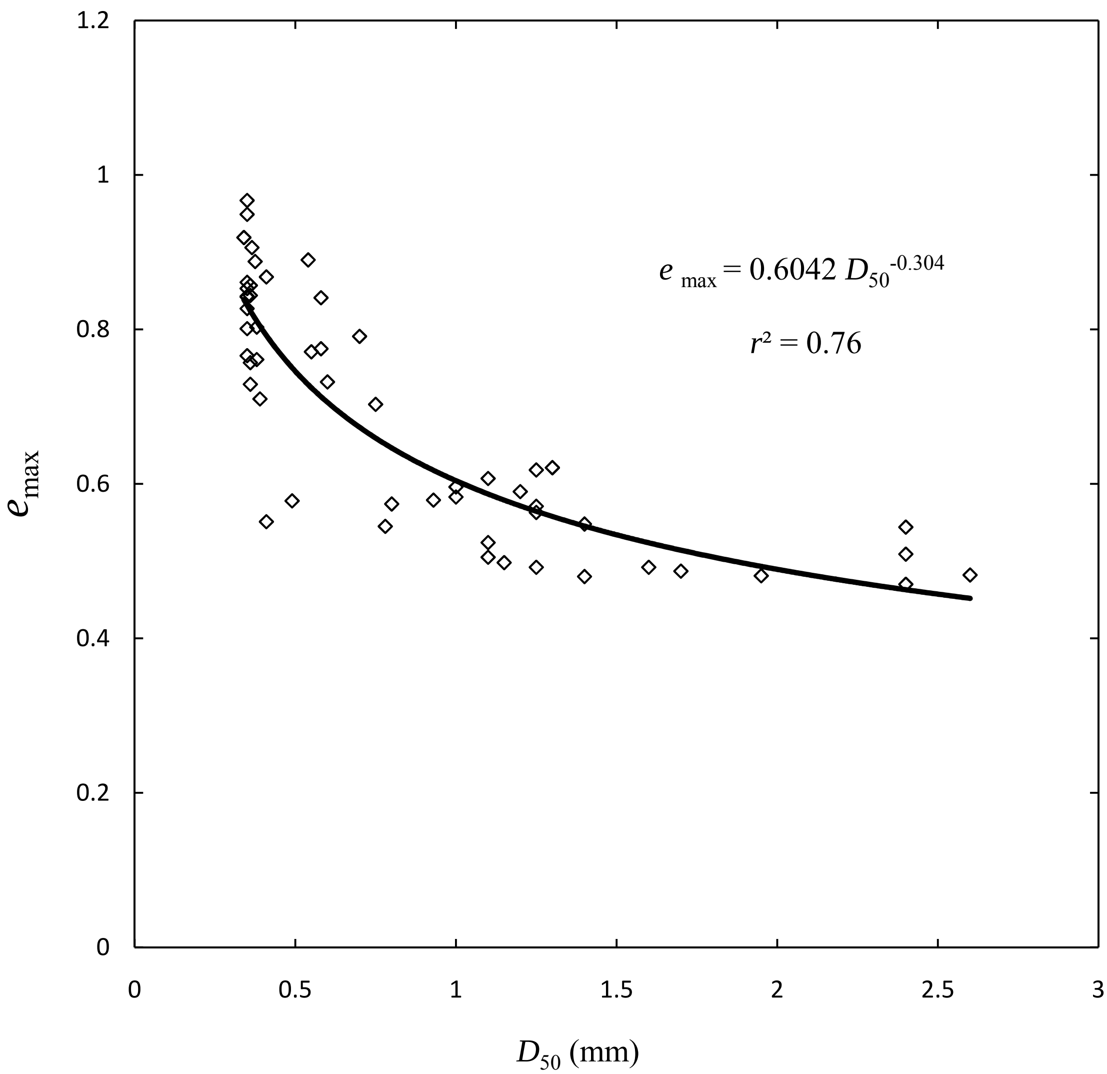


Figure 4.2: Variation of e_{max} with D_{50}

4.1.2 Prediction of minimum void ratio (e_{min}) from mean grain size (D_{50})

The void ratio in the densest state (e_{min}) of 55 samples has been plotted against their corresponding mean grain size (D_{50}). Several equations have been tried to fit to these experimental data. However, the best fit line to these sets of data is shown in Figure 4.3.

$$e_{min} = 0.3346\ D_{50}^{\ -0.491} \tag{4.2}$$

$$r^2 = 0.85$$

The least square value is comparatively good than other set of equations. For the sake of space and brevity other equations are not shown here.

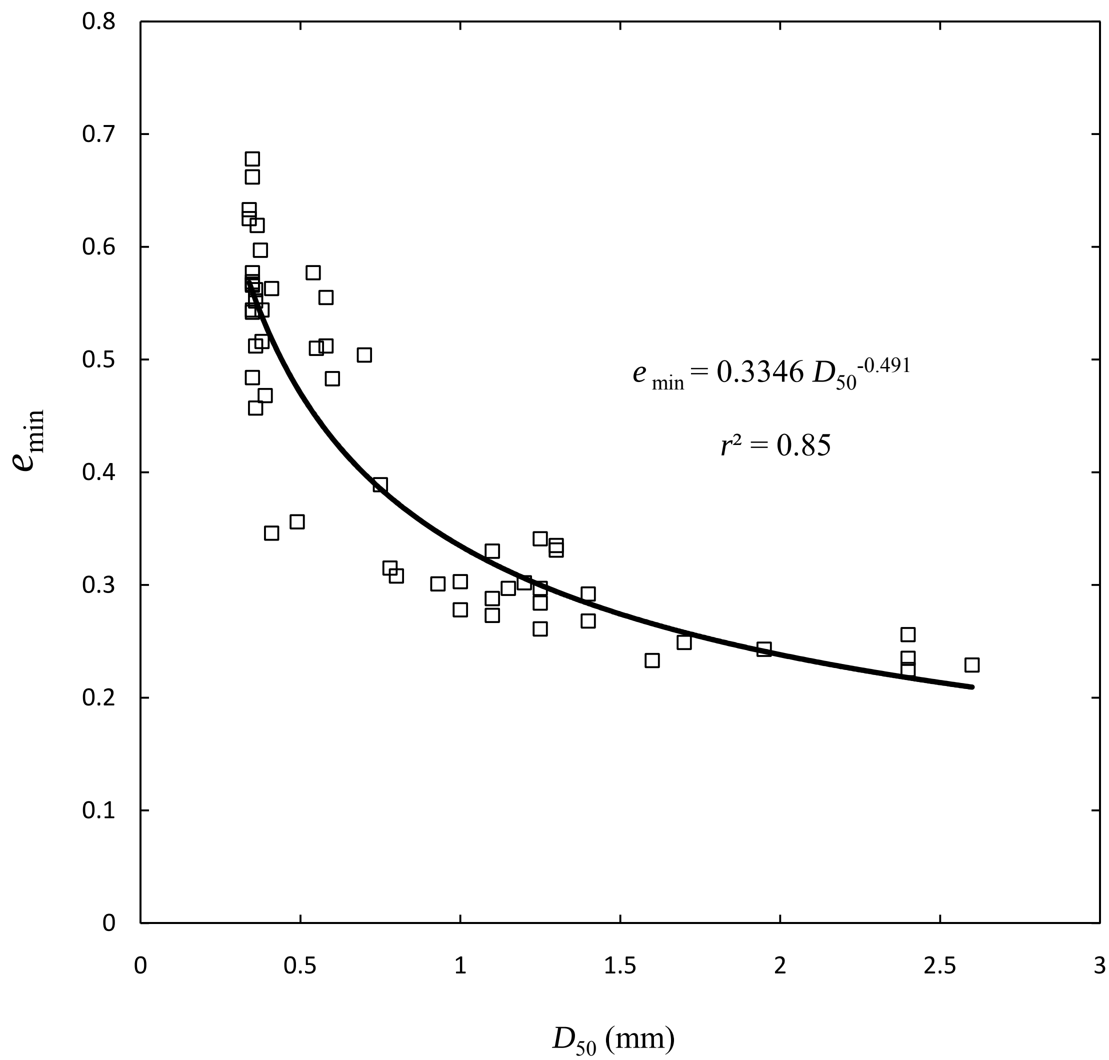


Figure 4.3: Variation of e_{min} with D_{50}

4.1.3 Prediction of void ratio range (e_{max} - e_{min}) from mean grain size (D_{50})

The void ratio range ($e_{max} - e_{min}$) of 55 samples has been plotted against their corresponding mean grain size (D_{50}). Several equations have been tried to fit to these experimental data. However, the best fit line to these sets of data is shown in Figure 4.4.

$$e_{max} - e_{min} = 0.26 + 0.007 / D_{50} \quad (4.3)$$

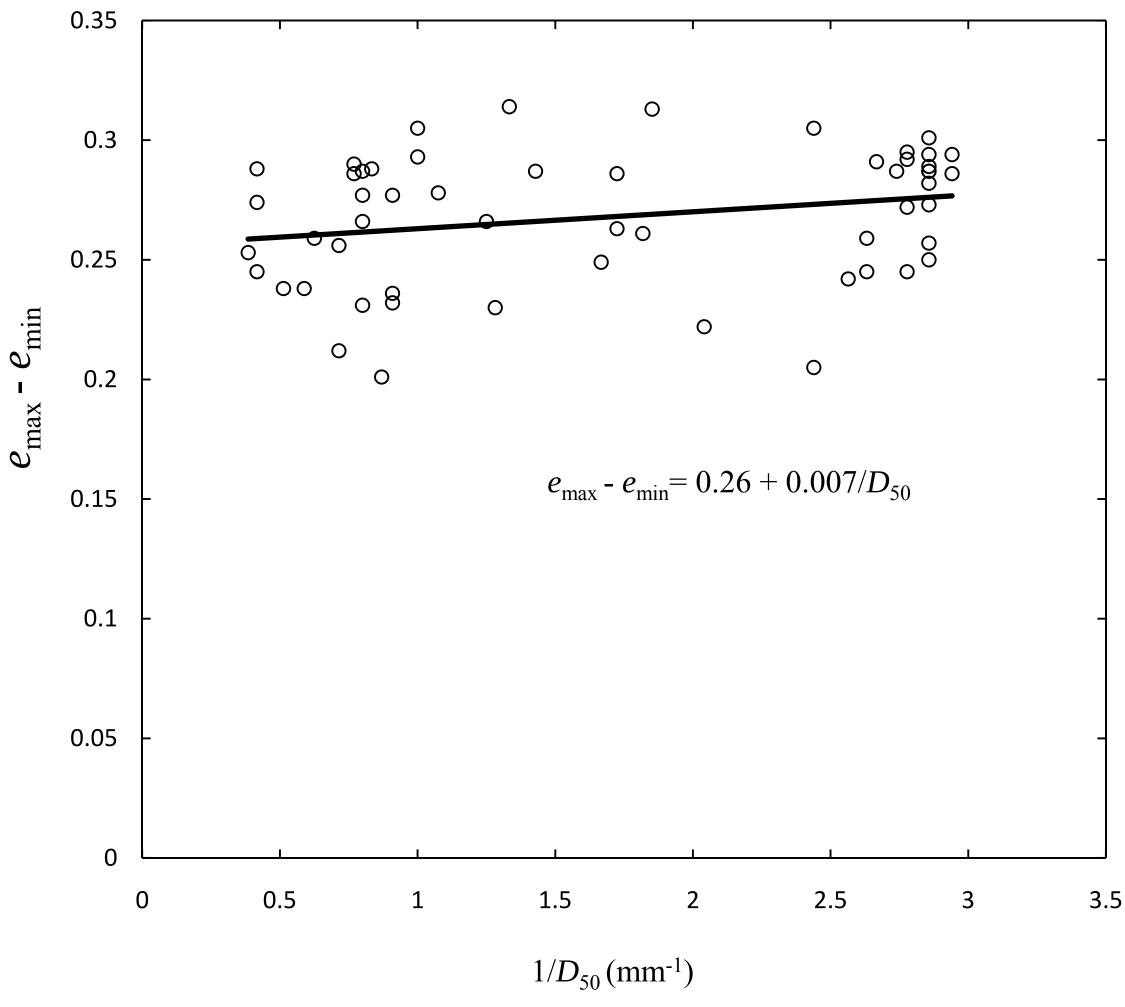


Figure 4.4: Variation of experimental ($e_{max} - e_{min}$) with 1/D_{50}

4.1.4 Prediction of maximum void ratio (e_{max}) from minimum void ratio (e_{min})

The void ratio in the loosest state (e_{max}) of 55 samples has been plotted against their corresponding void ratio in the densest state (e_{min}). Linear equation has been tried to fit to these experimental data and the best fit line to these sets of data is shown in Figure 4.5.

$$e_{max} = 1.0829\ e_{min} + 0.2331 \qquad (4.4)$$

$$r^2 = 0.97$$

The least square value is good. Evidently there is well defined correlation between e_{max} and e_{min}. Therefore, by knowing the e_{min} value, it is possible to predict e_{max} of a particular sand sample and vice versa.

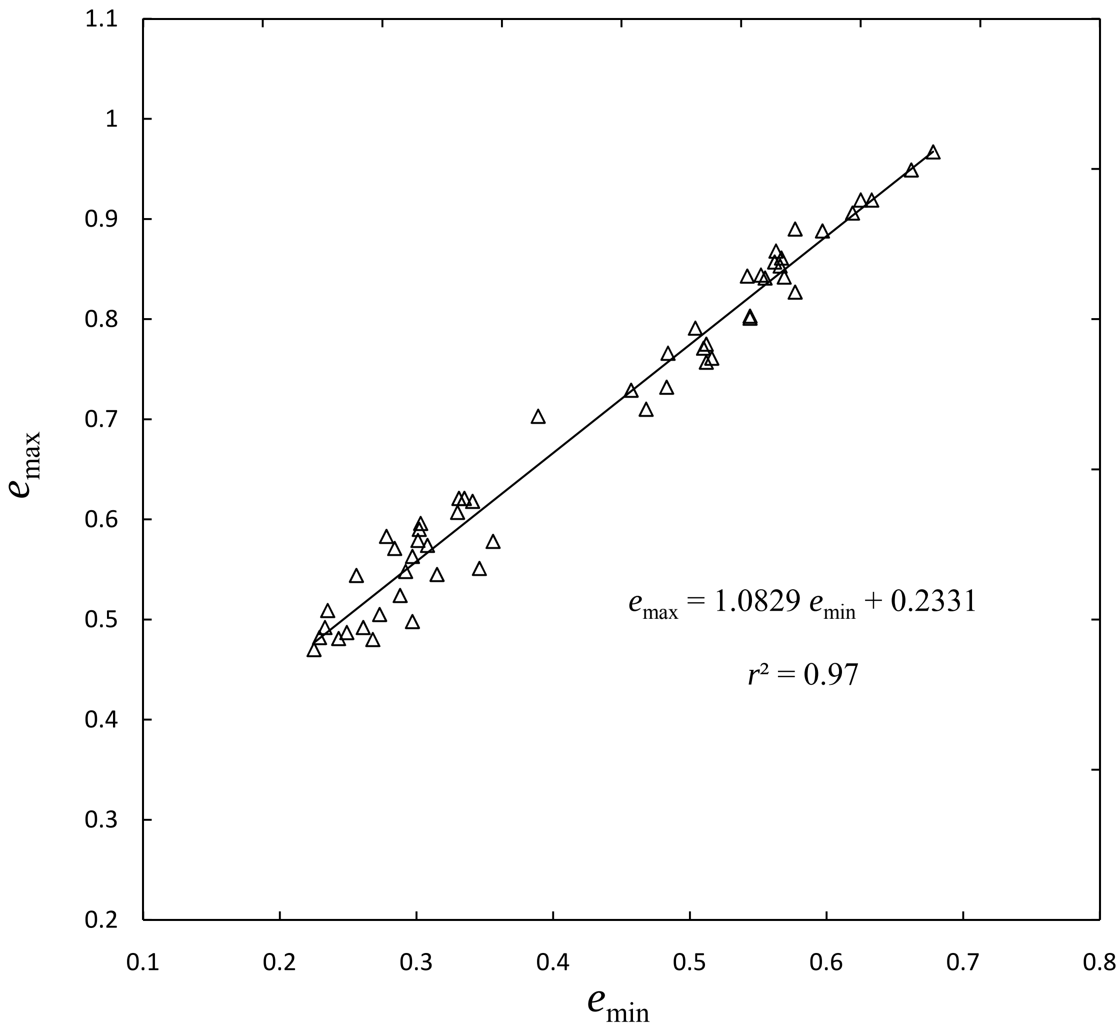


Figure 4.5: Variation of e_{max} with e_{min}

4.1.5 Comparison of results of present study with previous work

Cubrinovski and Ishihara (1999, 2002) studied the maximum and minimum void ratio characteristics of sands. Characteristics of the maximum and minimum void ratio of sands and their possible use for material characterization have been investigated in their study. Data of over 300 natural sandy soils including silty soils, clean sands, gravelly sands, gravels, sands with fines and sands containing small amount of clay-size particles have been used to examine the influence of fines, grain-size composition and particle shape on e_{max}, e_{min} and void ratio range (e_{max} - e_{min}). A set of empirical correlations were presented which clearly demonstrate the link between these void ratios and material properties of sands. They also studied the influence of mean grain size on maximum void ratio. They have suggested that maximum void ratio (e_{max}) increases with a decrease in the mean grain size (D_{50}) of the soil with the tendency being more pronounced for fine grained soils indicating the importance of fines content and plasticity of fines in the packing of fine soils. They have also established the relationship between e_{max} and $e_{min.}$ Therefore, they concluded that a similar correlation exists between e_{min} and $D_{50.}$

A comparison of the results on the maximum void ratio (e_{max}) and minimum void ratio (e_{min}) of present study with those reported by Cubrinovski and Ishihara (2002) has been presented in Figure 4.6 and 4.7. Cubrinovski and Ishihara (2002) considered 49 clean sands of mean grain size (D_{50}) varying from 0.15 to 0.83. The present data of 55 clean sands with D_{50} varying from 0.34 to 2.6 have been plotted in the same figure. Cubrinovski and Ishihara (2002) neither suggested any empirical equations for e_{max} with D_{50} or e_{min} with D_{50}. However, in this present study an attempted has been made to establish correlation between e_{max} with D_{50} and e_{min} with $D_{50.}$

The empirical equation predicted by present data points for e_{max} and e_{min} are as follows:

$$e_{max} = 0.6042\ D_{50}{}^{-0.304} \tag{4.5}$$

$$r^2 = 0.76$$

$$e_{min} = 0.3346\ D_{50}{}^{-0.491} \tag{4.6}$$

$$r^2 = 0.85$$

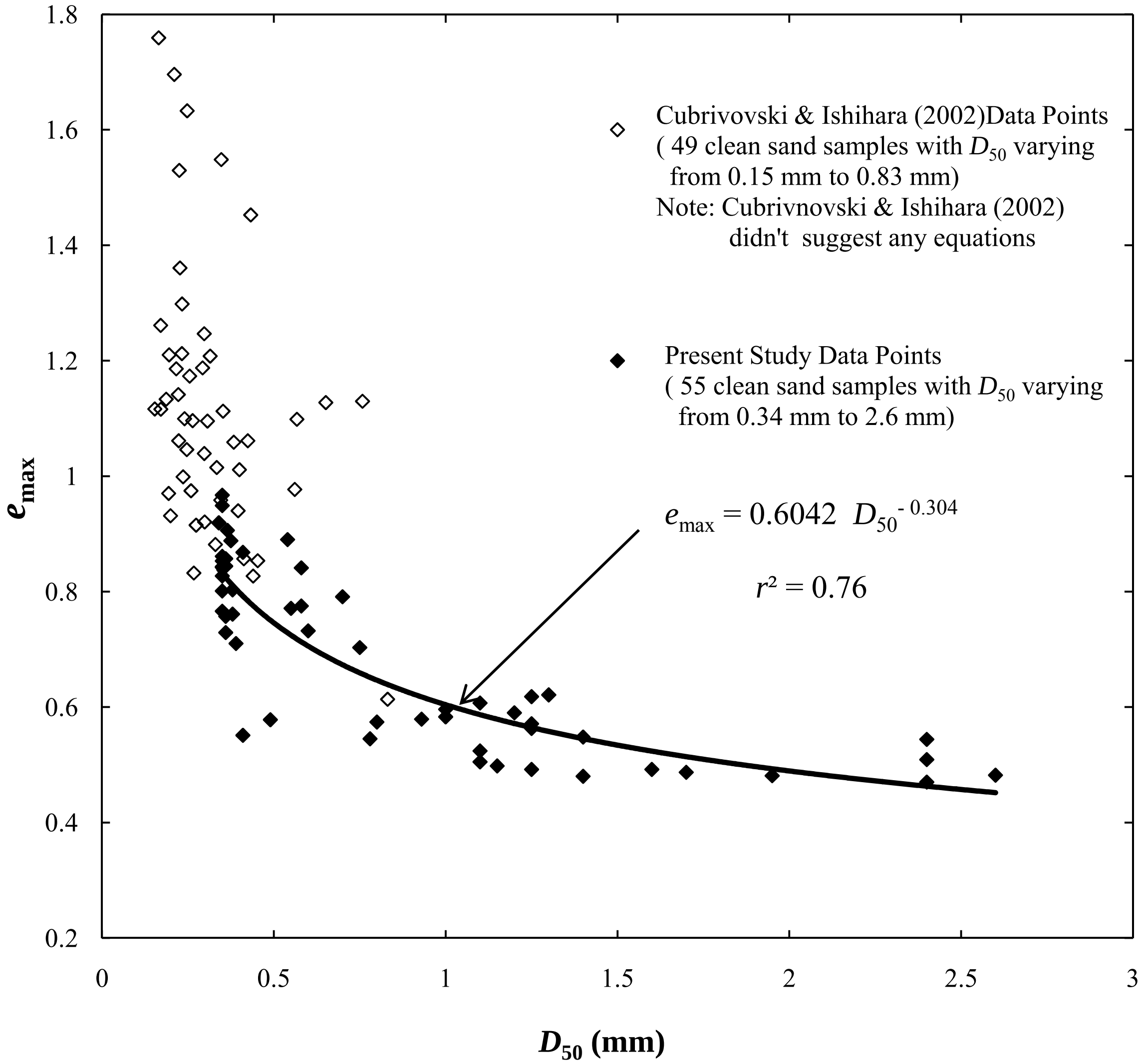


Figure 4.6: Present test data points along with the data points of Cubrinovski and Ishihara (2002) for e_{max} with D_{50}

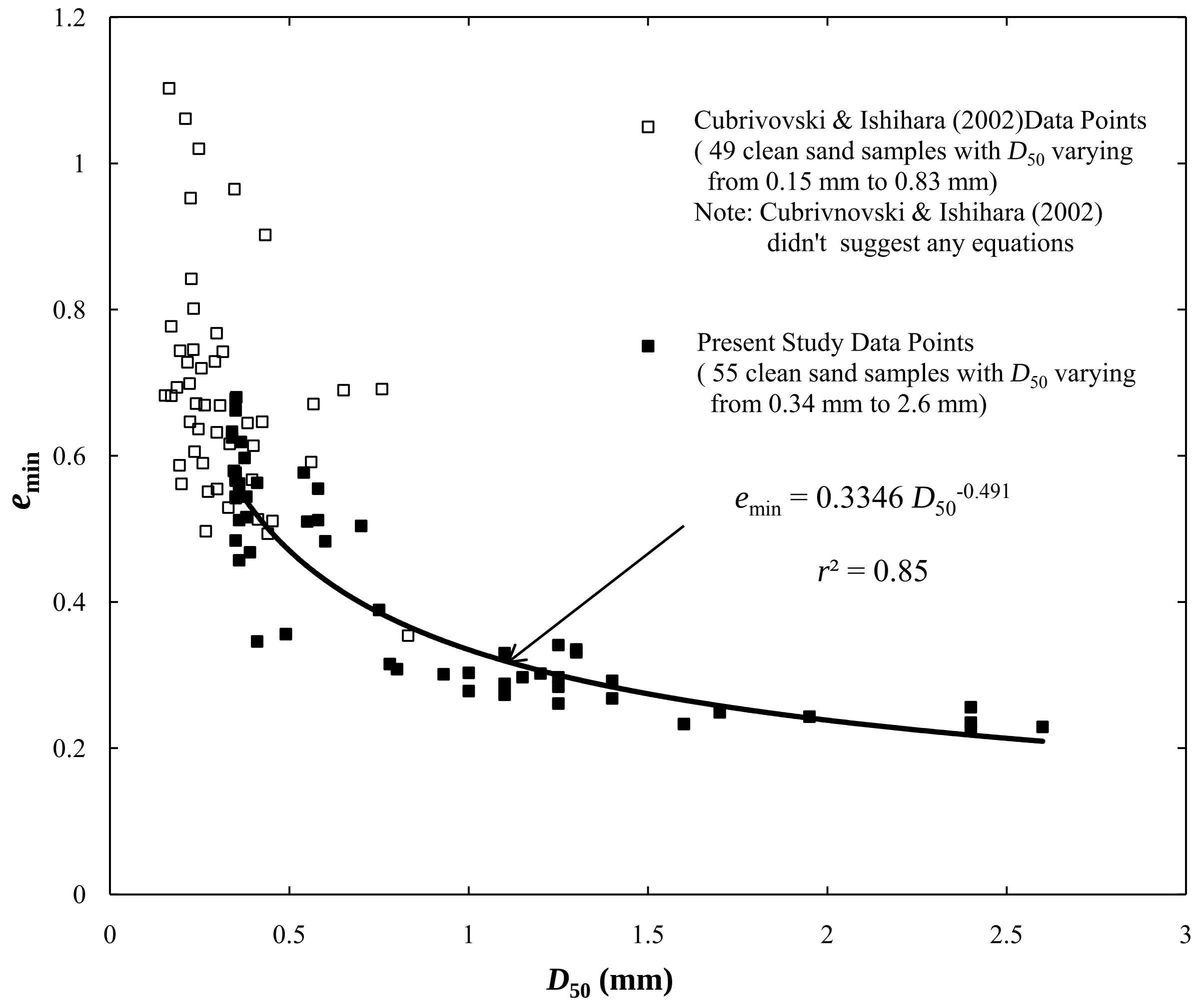


Figure 4.7: Present test data points along with the data points of Cubrinovski and Ishihara (2002) for e_{min} with D_{50}

Another comparison of the results on the voids ratio range of present study with those reported by Cubrinovski and Ishihara (1999) have been presented in Figure 4.8. Results of Cubrinovski and Ishihara (1999) fall in a band of curve by considering various types of soils. They considered the clean sands of mean grain size (D_{50}) vary from 0.15 to 0.83. The present data of clean sands with D_{50} vary from 0.34 to 2.6 have been plotted in the same figure. It is seen that the present data points fall within the band predicted by Cubrinovski and Ishihara (1999). Therefore, the empirical equation predicted by Cubrinovski and Ishihara (1999) will also valid for the present data points.

The empirical equation for (e_{max} - e_{min}) given by Cubrinovski and Ishihara (1999) for silty soils, sands with clays, sands with fines, clean sands, gravelly sands and gravels.

$$e_{max} - e_{min} = 0.23 + 0.06 / D_{50} \tag{4.7}$$

The empirical equation predicted by present data points only for clean sands is as follows:

$$e_{max} - e_{min} = 0.26 + 0.007 / D_{50} \tag{4.8}$$

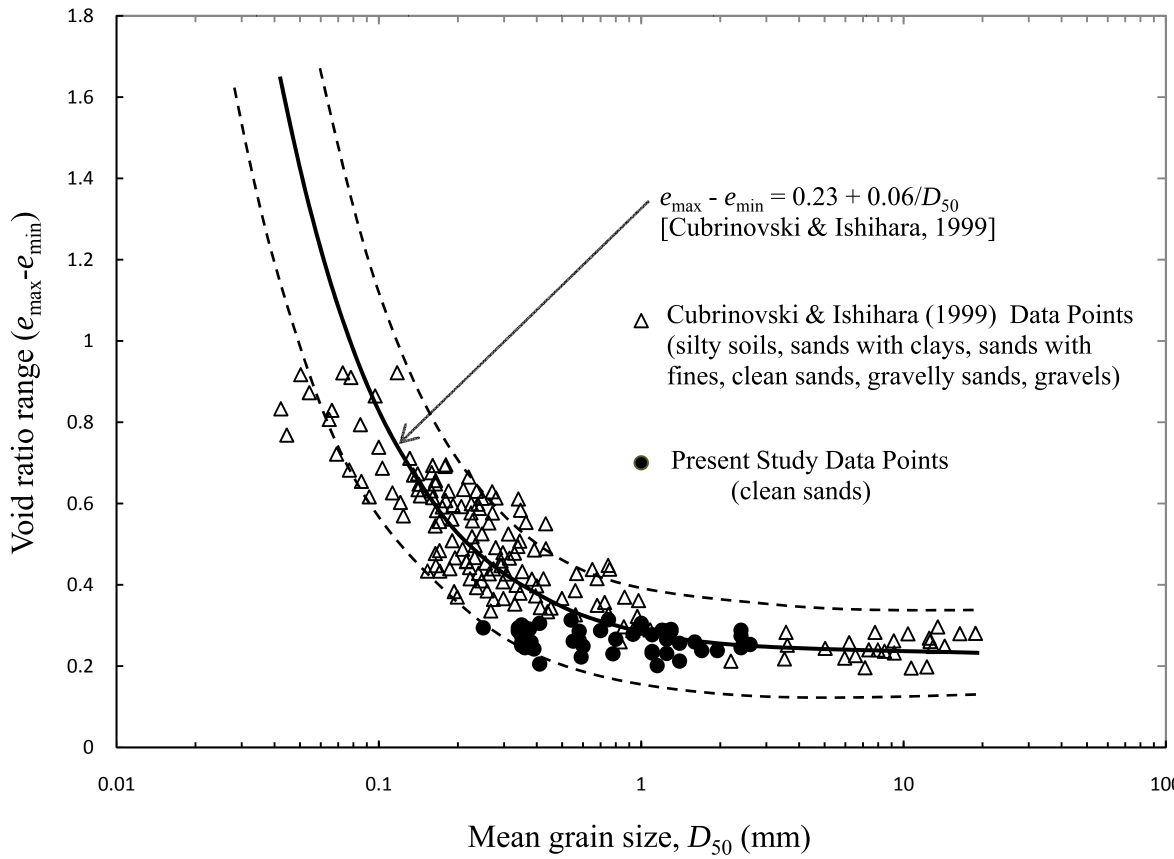


Figure 4.8: Present test data points along with the data points of Cubrinovski and Ishihara (1999) for (e_{max} –e_{min}) with D_{50}

By considering 49 number clean sand samples with D_{50} varying from 0.15 mm to 0.83 mm, the empirical equation for predicting e_{max} from e_{min} is given by Cubrinovski and Ishihara (2002) as follows:

$$e_{\max} = 1.53\, e_{\min} + 0.072 \tag{4.9}$$

$$r^2 = 0.97$$

The empirical equation for predicting e_{max} from e_{min} has been obtained from present data points considering 55 clean sand samples with D_{50} ranging from 0.34 mm to 2.6 mm is as follows:

$$e_{\max} = 1.0829\, e_{\min} + 0.2331 \tag{4.10}$$

$$r^2 = 0.97$$

The above aspects are shown in Figure 4.9.

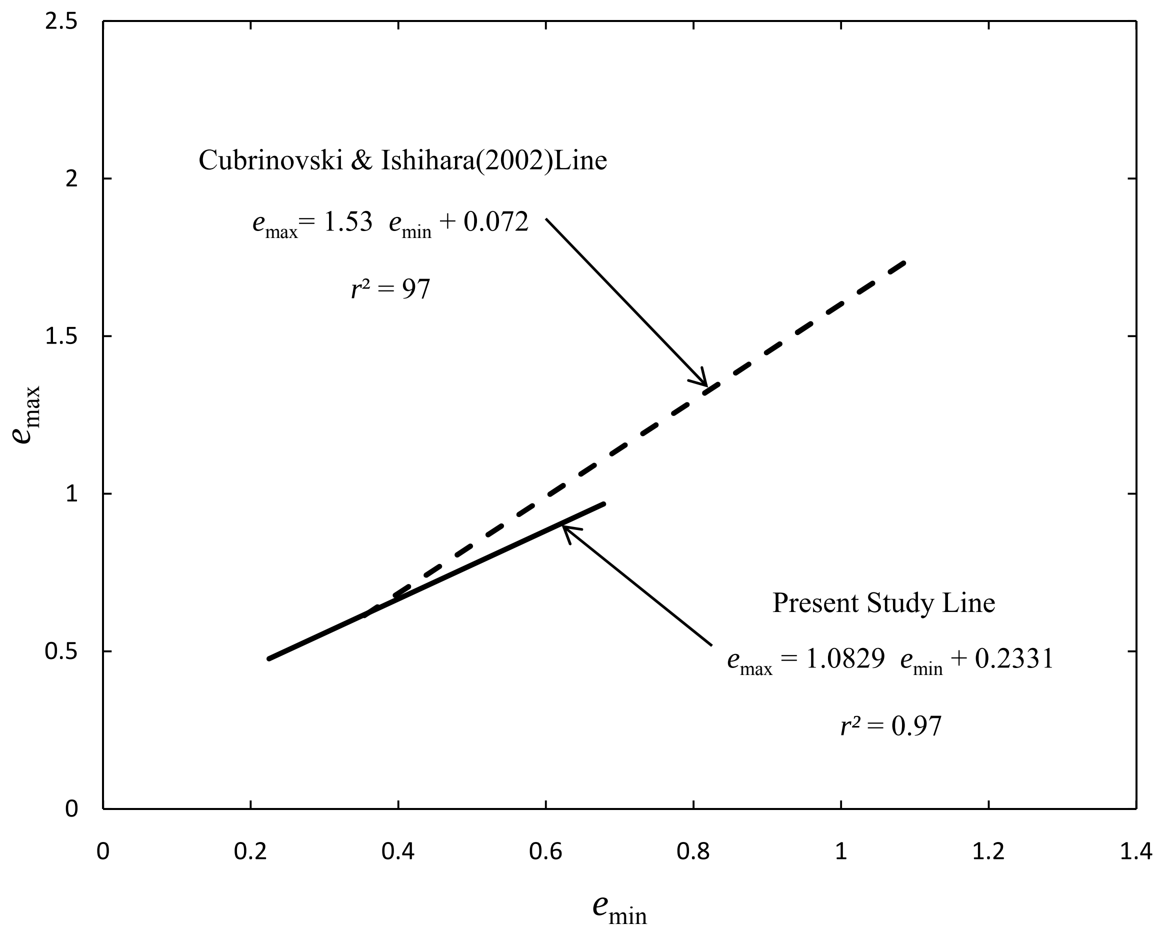


Figure 4.9: Relationship between e_{max} and e_{min} of clean sands of present study along with Cubrinovski and Ishihara (2002)

4.2 RELATIVE DENSITY FROM STANDARD & MODIFIED PROCTOR TEST

Laboratory standard and modified Proctor compaction test have been conducted on 28 sand samples starting from 0 % water content. It has been seen that at lower water content the nature of compaction curve was ill-defined. Therefore, rest of the compaction test for standard, modified Proctor tests have been carried out by starting water content 4 % or 6 %. All the compaction figures of 55 samples have been plotted in Appendix – A. Void ratio calculated from MDD corresponding to standard and modified Proctor tests have been used to determine relative densities described in Chapter 3 (Clause No.3.2.5). The values of relative density obtained from standard and modified Proctor tests are shown in Table 4.2 and 4.3 respectively.

Table 4.2 Experimental Relative Density with reference to Standard Proctor Test

Sample No.	e_{max} (Eq.3.6)	e_{min} (Eq.3.8)	e_{max} - e_{min}	$(\gamma_d)_s$	e_s (Eq.3.13)	$e_{max} - e_s$	$(D_r)_s$ (Eq.3.15)
1	0.791	0.504	0.287	1.63	0.612	0.179	62.49
2	0.949	0.662	0.287	1.554	0.754	0.195	67.88
3	0.775	0.512	0.263	1.652	0.607	0.168	63.82
4	0.967	0.678	0.289	1.53	0.768	0.199	68.87
5	0.771	0.51	0.261	1.68	0.617	0.154	58.90
6	0.868	0.563	0.305	1.61	0.675	0.193	63.23
7	0.888	0.597	0.291	1.638	0.687	0.201	68.93
8	0.906	0.619	0.287	1.6	0.706	0.200	69.82
9	0.89	0.577	0.313	1.56	0.688	0.202	64.39
10	0.703	0.389	0.314	1.78	0.531	0.172	54.63
11	0.766	0.484	0.282	1.67	0.586	0.180	63.75
12	0.841	0.555	0.286	1.6	0.658	0.184	64.16
13	0.844	0.552	0.292	1.647	0.641	0.203	69.67
14	0.827	0.577	0.25	1.63	0.652	0.175	69.94
15	0.803	0.544	0.259	1.66	0.633	0.170	65.59
16	0.801	0.544	0.257	1.66	0.624	0.177	68.83
17	0.732	0.483	0.249	1.7	0.581	0.151	60.57
18	0.761	0.516	0.245	1.68	0.598	0.163	66.69
19	0.842	0.569	0.273	1.6	0.668	0.175	63.92
20	0.853	0.566	0.287	1.61	0.664	0.189	65.86
21	0.919	0.633	0.286	1.57	0.720	0.199	69.67
22	0.919	0.625	0.294	1.57	0.724	0.195	66.26
23	0.857	0.562	0.295	1.6	0.660	0.197	66.78
24	0.861	0.567	0.294	1.62	0.654	0.207	70.30
25	0.729	0.457	0.272	1.709	0.558	0.171	62.79
26	0.71	0.468	0.242	1.71	0.557	0.153	63.34
27	0.757	0.512	0.245	1.696	0.587	0.170	69.28
28	0.843	0.542	0.301	1.652	0.633	0.210	69.91

Sample No.	e_{max} (Eq.3.6)	e_{min} (Eq.3.8)	e_{max} - e_{min}	$(\gamma_d)_s$	e_s (Eq.3.13)	$e_{max} - e_s$	$(D_r)_s$ (Eq.3.15)
29	0.509	0.235	0.274	1.909	0.355	0.154	56.15
30	0.505	0.273	0.232	1.89	0.370	0.135	58.03
31	0.482	0.229	0.253	1.94	0.335	0.147	58.29
32	0.481	0.243	0.238	1.92	0.347	0.134	56.36
33	0.544	0.256	0.288	1.878	0.376	0.168	58.36
34	0.492	0.233	0.259	1.93	0.343	0.149	57.53
35	0.487	0.249	0.238	1.92	0.348	0.139	58.22
36	0.48	0.268	0.212	1.91	0.353	0.127	59.96
37	0.47	0.225	0.245	1.941	0.328	0.142	57.89
38	0.578	0.356	0.222	1.78	0.447	0.131	59.18
39	0.583	0.278	0.305	1.822	0.417	0.166	54.57
40	0.545	0.315	0.23	1.815	0.419	0.126	54.66
41	0.596	0.303	0.293	1.792	0.440	0.156	53.14
42	0.574	0.308	0.266	1.79	0.428	0.146	54.91
43	0.579	0.301	0.278	1.814	0.428	0.151	54.39
44	0.563	0.297	0.266	1.82	0.414	0.149	55.91
45	0.548	0.292	0.256	1.852	0.408	0.140	54.82
46	0.551	0.346	0.205	1.82	0.429	0.122	59.45
47	0.498	0.297	0.201	1.89	0.385	0.113	56.39
48	0.492	0.261	0.231	1.871	0.367	0.125	54.26
49	0.59	0.302	0.288	1.809	0.418	0.172	59.56
50	0.524	0.288	0.236	1.866	0.379	0.145	61.26
51	0.621	0.331	0.29	1.735	0.462	0.159	54.74
52	0.621	0.335	0.286	1.729	0.466	0.155	54.14
53	0.618	0.341	0.277	1.737	0.470	0.148	53.30
54	0.607	0.33	0.277	1.76	0.457	0.150	54.22
55	0.571	0.284	0.287	1.807	0.414	0.157	54.53

Table 4.3 Experimental Relative Density with reference Modified Proctor Test

Sample No.	e_{max} (Eq.3.6)	e_{min} (Eq.3.8)	e_{max} - e_{min}	$(\gamma_d)_m$	e_m (Eq.3.13)	$e_{max} - e_m$	$(D_r)_m$ (Eq.3.16)
1	0.791	0.504	0.287	1.7	0.545	0.246	85.61
2	0.949	0.662	0.287	1.605	0.698	0.251	87.30
3	0.775	0.512	0.263	1.721	0.543	0.232	88.32
4	0.967	0.678	0.289	1.597	0.694	0.273	94.53
5	0.771	0.51	0.261	1.741	0.561	0.210	80.61
6	0.868	0.563	0.305	1.695	0.591	0.277	90.77
7	0.888	0.597	0.291	1.697	0.629	0.259	89.09
8	0.906	0.619	0.287	1.67	0.634	0.272	94.73
9	0.89	0.577	0.313	1.627	0.619	0.271	86.60
10	0.703	0.389	0.314	1.877	0.452	0.251	79.84
11	0.766	0.484	0.282	1.75	0.514	0.252	89.46

Sample No.	e_{max} (Eq.3.6)	e_{min} (Eq.3.8)	e_{max} - e_{min}	$(\gamma_d)_m$	e_m (Eq.3.13)	$e_{max} - e_m$	$(D_r)_m$ (Eq.3.16)
12	0.841	0.555	0.286	1.645	0.612	0.229	80.01
13	0.844	0.552	0.292	1.704	0.586	0.258	88.47
14	0.827	0.577	0.25	1.69	0.593	0.234	93.40
15	0.803	0.544	0.259	1.731	0.566	0.237	91.45
16	0.801	0.544	0.257	1.73	0.558	0.243	94.40
17	0.732	0.483	0.249	1.765	0.523	0.209	83.96
18	0.761	0.516	0.245	1.749	0.535	0.226	92.41
19	0.842	0.569	0.273	1.69	0.579	0.263	96.45
20	0.853	0.566	0.287	1.7	0.576	0.277	96.56
21	0.919	0.633	0.286	1.64	0.646	0.273	95.34
22	0.919	0.625	0.294	1.659	0.632	0.287	97.72
23	0.857	0.562	0.295	1.689	0.573	0.284	96.43
24	0.861	0.567	0.294	1.7	0.576	0.285	96.78
25	0.729	0.457	0.272	1.8	0.479	0.250	91.75
26	0.71	0.468	0.242	1.799	0.480	0.230	95.16
27	0.757	0.512	0.245	1.77	0.521	0.236	96.37
28	0.843	0.542	0.301	1.73	0.559	0.284	94.37
29	0.509	0.235	0.274	2.01	0.287	0.222	81.00
30	0.505	0.273	0.232	1.97	0.315	0.190	82.02
31	0.482	0.229	0.253	2.03	0.275	0.207	81.67
32	0.481	0.243	0.238	2.011	0.286	0.195	81.96
33	0.544	0.256	0.288	1.98	0.305	0.239	82.97
34	0.492	0.233	0.259	2.02	0.283	0.209	80.63
35	0.487	0.249	0.238	2	0.295	0.193	80.88
36	0.48	0.268	0.212	1.981	0.304	0.176	82.83
37	0.47	0.225	0.245	2.04	0.264	0.206	84.19
38	0.578	0.356	0.222	1.86	0.384	0.194	87.20
39	0.583	0.278	0.305	1.92	0.344	0.239	78.27
40	0.545	0.315	0.23	1.89	0.363	0.182	79.15
41	0.596	0.303	0.293	1.888	0.367	0.229	78.14
42	0.574	0.308	0.266	1.87	0.367	0.207	77.88
43	0.579	0.301	0.278	1.9	0.363	0.216	77.64
44	0.563	0.297	0.266	1.9	0.355	0.208	78.29
45	0.548	0.292	0.256	1.933	0.349	0.199	77.86
46	0.551	0.346	0.205	1.89	0.376	0.175	85.27
47	0.498	0.297	0.201	1.97	0.328	0.170	84.36
48	0.492	0.261	0.231	1.96	0.305	0.187	81.13
49	0.59	0.302	0.288	1.912	0.342	0.248	86.09
50	0.524	0.288	0.236	1.953	0.318	0.206	87.30
51	0.621	0.331	0.29	1.811	0.401	0.220	75.90
52	0.621	0.335	0.286	1.808	0.402	0.219	76.54
53	0.618	0.341	0.277	1.83	0.396	0.222	80.28
54	0.607	0.33	0.277	1.84	0.393	0.214	77.08
55	0.571	0.284	0.287	1.9	0.345	0.226	78.65

4.2.1 Prediction of void ratio corresponding to standard Proctor test (e_s) from mean grain size (D_{50})

The void ratio corresponding to standard Proctor test (e_s) of 55 samples has been plotted against their corresponding mean grain size (D_{50}). Several equations have been tried to fit to these experimental data. However, the best fit line to these sets of data is shown in Figure 4.10.

$$e_s = 0.4484\ D_{50}^{\ -0.356} \tag{4.11}$$

$$r^2 = 0.80$$

The least square value is comparatively good than other set of equations. For the sake of space and brevity other equations are not shown here.

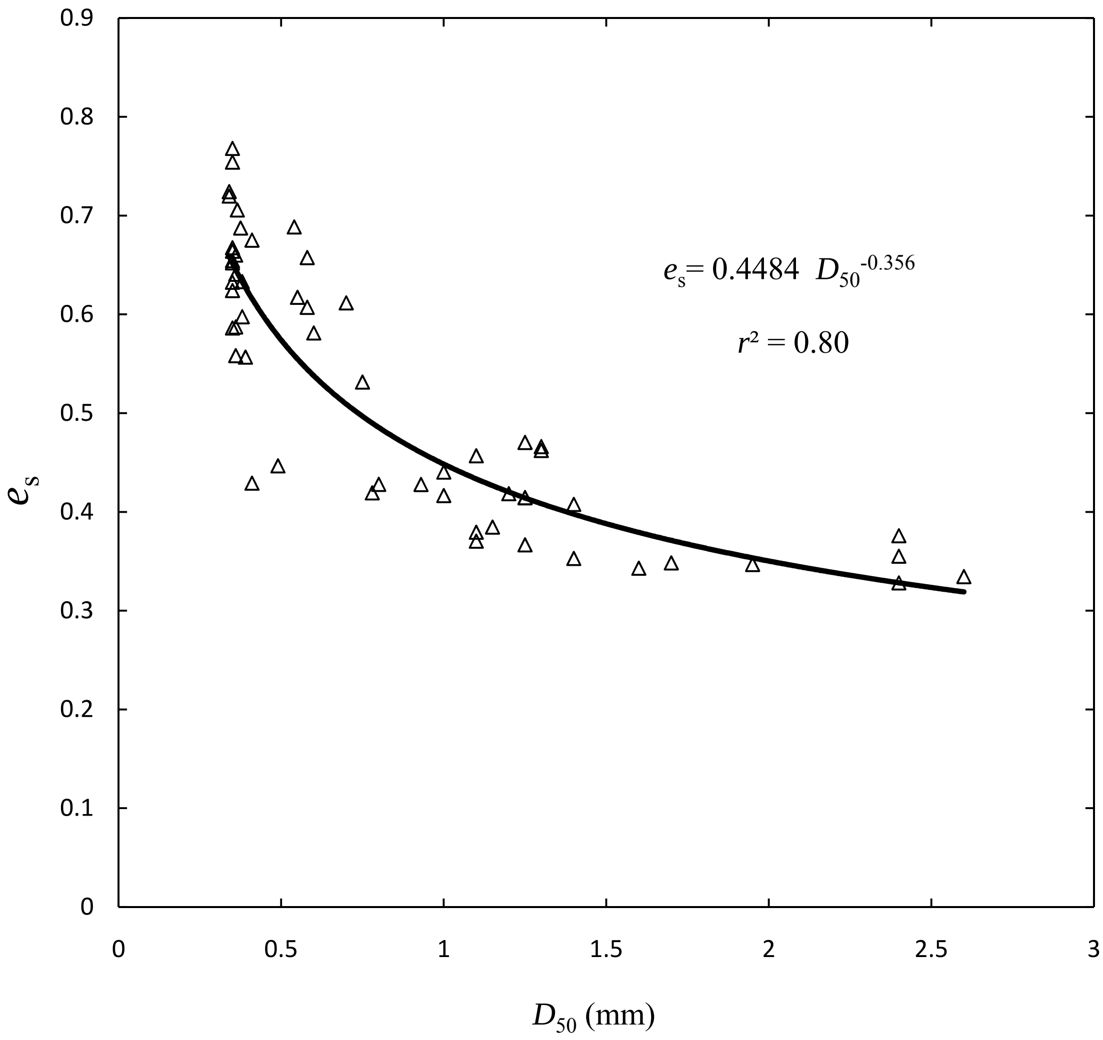


Figure 4.10: Variation of e_s with D_{50}

4.2.2 Prediction of void ratio corresponding to modified Proctor test (e_m) from mean grain size (D_{50})

The void ratio corresponding to modified Proctor test (e_m) of 55 samples has been plotted against their corresponding mean grain size (D_{50}). Several equations have been tried to fit to these experimental data. However, the best fit line to these sets of data is shown in Figure 4.11.

$$e_m = 0.3825\, D_{50}^{-0.4} \tag{4.12}$$

$$r^2 = 0.81$$

The least square value is comparatively good than other set of equations. For the sake of space and brevity other equations are not shown here.

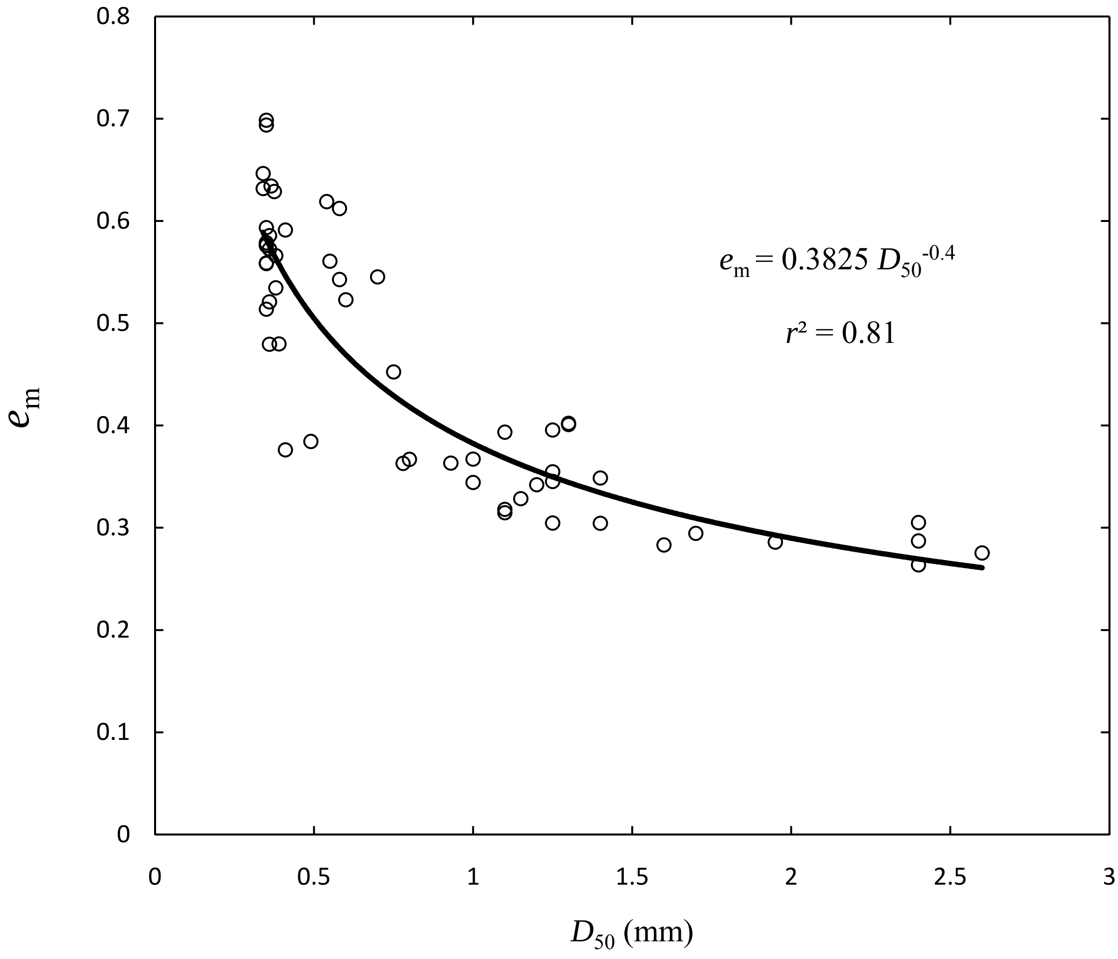


Figure 4.11: Variation of e_m with D_{50}

4.2.3 Prediction of Relative Density (D_r)

The void ratios like e_{max}, e_{min}, e_s and e_m are empirically correlated with D_{50}. From the empirical relations of e_{max}, e_{min}, e_s and e_m as obtained earlier (Eq. 4.1, 4.2, 4.11, and 4.12) has been utilized to predict the relative density of sand from D_{50} as follows:

Relative density corresponding to standard Proctor test, $(D_r)_s$

$$(D_r)_s = \frac{e_{\max} - e_s}{e_{\max} - e_{\min}} \times 100 = \frac{0.6042 D_{50}{}^{-0.304} - 0.4484 D_{50}{}^{-0.356}}{0.6042 D_{50}{}^{-0.304} - 0.3346 D_{50}{}^{-0.491}} \times 100 \tag{4.13}$$

where

$$e_{\max} = 0.6042 D_{50}{}^{-0.304}$$
$$e_{\min} = 0.3346 D_{50}{}^{-0.491}$$
$$e_s = 0.4484 D_{50}{}^{-0.356}$$

Relative density corresponding to modified Proctor test, $(D_r)_m$

$$(D_r)_m = \frac{e_{\max} - e_m}{e_{\max} - e_{\min}} \times 100 = \frac{0.6042 D_{50}{}^{-0.304} - 0.3825 D_{50}{}^{-0.400}}{0.6042 D_{50}{}^{-0.304} - 0.3346 D_{50}{}^{-0.491}} \times 100 \tag{4.14}$$

where

$$e_{\max} = 0.6042 D_{50}{}^{-0.304}$$
$$e_{\min} = 0.3346 D_{50}{}^{-0.491}$$
$$e_m = 0.3825 D_{50}{}^{-0.4}$$

The relative density predicted by conducting Standard and Modified Proctors tests by using Eq. (4.13, 4.14) are shown in Table 4.4 and Table 4.5 respectively.

Table 4.4: Predicted Relative Density with reference Standard Proctor Test

Sample No.	**Predicted e_{max}**	**Predicted e_{min}**	**Predicted e_{max} - e_{min}**	**Predicted e_s**	**Predicted $e_{max} - e_s$**	**Predicted $(D_r)_s$ (%)**
1	0.673	0.399	0.275	0.509	0.164	59.79
2	0.831	0.560	0.271	0.652	0.180	66.31
3	0.713	0.437	0.276	0.544	0.169	61.15
4	0.831	0.560	0.271	0.652	0.180	66.31
5	0.725	0.449	0.276	0.555	0.170	61.58
6	0.792	0.518	0.274	0.616	0.176	64.40
7	0.814	0.542	0.272	0.636	0.178	65.44
8	0.821	0.549	0.272	0.642	0.179	65.77
9	0.729	0.453	0.276	0.558	0.170	61.73
10	0.659	0.385	0.274	0.497	0.163	59.35
11	0.831	0.560	0.271	0.652	0.180	66.31
12	0.713	0.437	0.276	0.544	0.169	61.15
13	0.824	0.553	0.272	0.645	0.179	65.94
14	0.831	0.560	0.271	0.652	0.180	66.31
15	0.811	0.538	0.273	0.633	0.178	65.28
16	0.831	0.560	0.271	0.652	0.180	66.31
17	0.706	0.430	0.276	0.538	0.168	60.89
18	0.811	0.538	0.273	0.633	0.178	65.28
19	0.831	0.560	0.271	0.652	0.180	66.31
20	0.831	0.560	0.271	0.652	0.180	66.31
21	0.839	0.568	0.270	0.658	0.180	66.69
22	0.839	0.568	0.270	0.658	0.180	66.69
23	0.824	0.553	0.272	0.645	0.179	65.94
24	0.831	0.560	0.271	0.652	0.180	66.31
25	0.824	0.553	0.272	0.645	0.179	65.94
26	0.804	0.531	0.273	0.627	0.177	64.97
27	0.824	0.553	0.272	0.645	0.179	65.94
28	0.831	0.560	0.271	0.652	0.180	66.31
29	0.463	0.218	0.245	0.328	0.135	54.90
30	0.587	0.319	0.268	0.433	0.154	57.35
31	0.452	0.209	0.243	0.319	0.133	54.74
32	0.493	0.241	0.252	0.354	0.140	55.39
33	0.463	0.218	0.245	0.328	0.135	54.90
34	0.524	0.266	0.258	0.379	0.144	55.96
35	0.514	0.258	0.256	0.371	0.143	55.78
36	0.545	0.284	0.262	0.398	0.148	56.41
37	0.463	0.218	0.245	0.328	0.135	54.90

Sample No.	Predicted e_{max}	Predicted e_{min}	Predicted e_{max} - e_{min}	Predicted e_s	Predicted $e_{max} - e_s$	Predicted $(D_r)_s$ (%)
38	0.751	0.475	0.276	0.578	0.172	62.59
39	0.604	0.335	0.270	0.448	0.156	57.79
40	0.652	0.378	0.274	0.490	0.162	59.12
41	0.604	0.335	0.270	0.448	0.156	57.79
42	0.647	0.373	0.273	0.485	0.161	58.97
43	0.618	0.347	0.271	0.460	0.158	58.15
44	0.565	0.300	0.265	0.414	0.150	56.83
45	0.545	0.284	0.262	0.398	0.148	56.41
46	0.792	0.518	0.274	0.616	0.176	64.40
47	0.579	0.312	0.267	0.427	0.152	57.16
48	0.565	0.300	0.265	0.414	0.150	56.83
49	0.572	0.306	0.266	0.420	0.151	56.99
50	0.587	0.319	0.268	0.433	0.154	57.35
51	0.558	0.294	0.264	0.408	0.149	56.68
52	0.558	0.294	0.264	0.408	0.149	56.68
53	0.565	0.300	0.265	0.414	0.150	56.83
54	0.587	0.319	0.268	0.433	0.154	57.35
55	0.565	0.300	0.265	0.414	0.150	56.83

Table 4.5: Predicted Relative Density with reference Modified Proctor Test

Sample No.	Predicted e_{max}	Predicted e_{min}	Predicted e_{max} - e_{min}	Predicted e_m	Predicted e_{max} - e_m	Predicted $(D_r)_m$(%)
1	0.673	0.399	0.275	0.441	0.232	84.53
2	0.831	0.560	0.271	0.582	0.249	91.94
3	0.713	0.437	0.276	0.476	0.237	86.07
4	0.831	0.560	0.271	0.582	0.249	91.94
5	0.725	0.449	0.276	0.486	0.239	86.56
6	0.792	0.518	0.274	0.546	0.246	89.77
7	0.814	0.542	0.272	0.566	0.248	90.95
8	0.821	0.549	0.272	0.572	0.248	91.33
9	0.729	0.453	0.276	0.489	0.239	86.73
10	0.659	0.385	0.274	0.429	0.230	84.02
11	0.831	0.560	0.271	0.582	0.249	91.94
12	0.713	0.437	0.276	0.476	0.237	86.07
13	0.824	0.553	0.272	0.576	0.249	91.53
14	0.831	0.560	0.271	0.582	0.249	91.94
15	0.811	0.538	0.273	0.563	0.248	90.77
16	0.831	0.560	0.271	0.582	0.249	91.94
17	0.706	0.430	0.276	0.469	0.236	85.77

Sample No.	Predicted e_{max}	Predicted e_{min}	Predicted e_{max} - e_{min}	Predicted e_m	Predicted e_{max} - e_m	Predicted $(D_r)_m$(%)
18	0.811	0.538	0.273	0.563	0.248	90.77
19	0.831	0.560	0.271	0.582	0.249	91.94
20	0.831	0.560	0.271	0.582	0.249	91.94
21	0.839	0.568	0.270	0.589	0.250	92.38
22	0.839	0.568	0.270	0.589	0.250	92.38
23	0.824	0.553	0.272	0.576	0.249	91.53
24	0.831	0.560	0.271	0.582	0.249	91.94
25	0.824	0.553	0.272	0.576	0.249	91.53
26	0.804	0.531	0.273	0.557	0.247	90.42
27	0.824	0.553	0.272	0.576	0.249	91.53
28	0.831	0.560	0.271	0.582	0.249	91.94
29	0.463	0.218	0.245	0.269	0.194	78.88
30	0.587	0.319	0.268	0.368	0.219	81.73
31	0.452	0.209	0.243	0.261	0.191	78.69
32	0.493	0.241	0.252	0.293	0.200	79.46
33	0.463	0.218	0.245	0.269	0.194	78.88
34	0.524	0.266	0.258	0.317	0.207	80.13
35	0.514	0.258	0.256	0.309	0.205	79.91
36	0.545	0.284	0.262	0.334	0.211	80.64
37	0.463	0.218	0.245	0.269	0.194	78.88
38	0.751	0.475	0.276	0.509	0.242	87.71
39	0.604	0.335	0.270	0.383	0.222	82.23
40	0.652	0.378	0.274	0.422	0.229	83.75
41	0.604	0.335	0.270	0.383	0.222	82.23
42	0.647	0.373	0.273	0.418	0.228	83.58
43	0.618	0.347	0.271	0.394	0.224	82.64
44	0.565	0.300	0.265	0.350	0.215	81.12
45	0.545	0.284	0.262	0.334	0.211	80.64
46	0.792	0.518	0.274	0.546	0.246	89.77
47	0.579	0.312	0.267	0.362	0.217	81.51
48	0.565	0.300	0.265	0.350	0.215	81.12
49	0.572	0.306	0.266	0.356	0.216	81.31
50	0.587	0.319	0.268	0.368	0.219	81.73
51	0.558	0.294	0.264	0.344	0.213	80.95
52	0.558	0.294	0.264	0.344	0.213	80.95
53	0.565	0.300	0.265	0.350	0.215	81.12
54	0.587	0.319	0.268	0.368	0.219	81.73
55	0.565	0.300	0.265	0.350	0.215	81.12

4.2.4 Comparison of predicted relative density with experimental values

The values of relative density obtained from the experimental standard and modified Proctor tests have been plotted against the predicted values obtained as a function of D_{50} are shown in Figure 4.12. The same has been presented in Table 4.6 for better comparison.

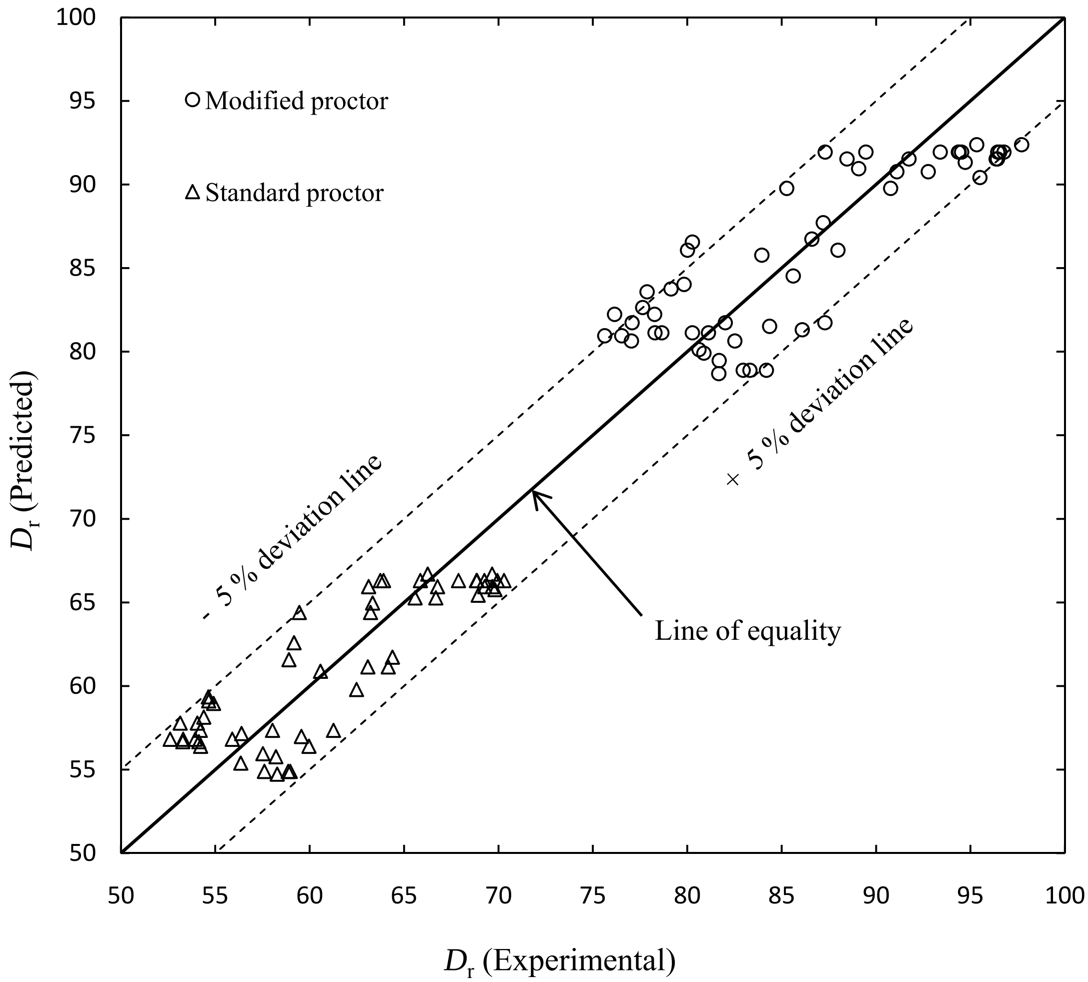


Figure 4.12: Plot of D_r (experimental) versus D_r (predicted)

Table 4.6: Percentage deviation between predicted and experimental relative density values

Sample No.	Standard Proctor Test			Modified Proctor Test		
	Predicted D_r	**Experimental D_r**	**% Deviation**	**Predicted D_r**	**Experimental D_r**	**% Deviation**
1	59.79	62.48	4.492	84.53	85.61	1.282
2	66.31	67.88	2.371	91.94	87.30	-5.047
3	61.15	63.08	3.158	86.07	87.98	2.218
4	66.31	68.86	3.849	91.94	94.53	2.817
5	61.58	58.90	-4.348	86.56	80.27	-7.266
6	64.40	63.22	-1.828	89.77	90.77	1.116
7	65.44	68.92	5.325	90.95	89.08	-2.054
8	65.77	69.81	6.143	91.33	94.72	3.714
9	61.73	64.38	4.292	86.73	86.60	-0.154
10	59.35	54.63	-7.959	84.02	79.83	-4.991
11	66.31	63.74	-3.873	91.94	89.46	-2.697
12	61.15	64.16	4.924	86.07	80.01	-7.042
13	65.94	69.67	5.650	91.53	88.46	-3.350
14	66.31	69.94	5.477	91.94	93.40	1.588
15	65.28	65.58	0.467	90.77	91.10	0.368
16	66.31	68.83	3.803	91.94	94.40	2.676
17	60.89	60.57	-0.520	85.77	83.95	-2.125
18	65.28	66.68	2.152	90.77	92.76	2.197
19	66.31	63.91	-3.617	91.94	96.44	4.895
20	66.31	65.86	-0.676	91.94	96.55	5.014
21	66.69	69.66	4.446	92.38	95.33	3.194
22	66.69	66.25	-0.667	92.38	97.71	5.771
23	65.94	66.77	1.253	91.53	96.43	5.358
24	66.31	70.29	6.005	91.94	96.77	5.254
25	65.94	63.12	-4.282	91.53	91.74	0.234
26	64.97	63.33	-2.520	90.42	95.50	5.623
27	65.94	69.27	5.044	91.53	96.36	5.282
28	66.31	69.25	4.437	91.94	94.36	2.632
29	54.90	58.97	7.411	78.88	83.32	5.622
30	57.35	58.03	1.178	81.73	82.01	0.339
31	54.74	58.28	6.475	78.69	81.67	3.789
32	55.39	56.35	1.725	79.46	81.69	2.800
33	54.90	58.86	7.210	78.88	82.96	5.166
34	55.96	57.52	2.785	80.13	80.62	0.618
35	55.78	58.21	4.363	79.91	80.88	1.213
36	56.41	59.96	6.303	80.64	82.52	2.332
37	54.90	57.60	4.915	78.88	84.19	6.725
38	62.59	59.17	-5.463	87.71	87.20	-0.582
39	57.79	54.05	-6.471	82.23	78.27	-4.819
40	59.12	54.65	-7.554	83.75	79.14	-5.506

Sample No.	Standard Proctor Test			Modified Proctor Test		
	Predicted D_r	Experimental D_r	% Deviation	Predicted D_r	Experimental D_r	% Deviation
41	57.79	53.14	-8.045	82.23	76.15	-7.397
42	58.97	54.91	-6.879	83.58	77.87	-6.833
43	58.15	54.39	-6.460	82.64	77.64	-6.053
44	56.83	55.90	-1.629	81.12	78.29	-3.495
45	56.41	54.22	-3.874	80.64	77.04	-4.464
46	64.40	59.45	-7.683	89.77	85.27	-5.011
47	57.16	56.39	-1.353	81.51	84.36	3.491
48	56.83	53.94	-5.078	81.12	81.12	-0.006
49	56.99	59.56	4.513	81.31	86.09	5.876
50	57.35	61.26	6.810	81.73	87.29	6.799
51	56.68	53.28	-5.991	80.95	75.63	-6.574
52	56.68	54.13	-4.491	80.95	76.53	-5.462
53	56.83	53.30	-6.204	81.12	80.27	-1.054
54	57.35	54.21	-5.482	81.73	77.08	-5.693
55	56.83	52.61	-7.419	81.12	78.65	-3.051

4.3 RELATIVE DENSITY FROM REDUCED STANDARD & MODIFIED PROCTOR TEST

Laboratory reduced standard and modified Proctor compaction test have been conducted on 55 sand samples starting from 4 % or 6 % water content. All the compaction test figures of 55 samples have been plotted in Appendix – A. Reduced standard Proctor and reduced modified Proctor tests have been conducted in the laboratory to determine relative densities. Void ratio calculated from MDD corresponding to standard and modified Proctor tests have been used to determine relative densities described in Chapter 3 (Clause No.3.2.5). The values of relative density obtained from standard and modified Proctor tests are shown in Table 4.7 and 4.8 respectively.

Table 4.7: Experimental Relative Density with reference to Reduced Standard Proctor Test

Sample No.	e_{max} (Eq.3.6)	e_{min} (Eq.3.8)	$e_{max} - e_{min}$	$(\gamma_d)_{rs}$	e_{rs} (Eq.3.13)	$e_{max} - e_{rs}$	$(D_r)_{rs}$ (Eq.3.17)
1	0.791	0.504	0.287	1.57	0.673	0.118	41.03
2	0.949	0.662	0.287	1.5	0.817	0.132	45.88
3	0.775	0.512	0.263	1.59	0.670	0.105	40.00
4	0.967	0.678	0.289	1.48	0.828	0.139	48.20
5	0.771	0.51	0.261	1.627	0.670	0.101	38.72
6	0.868	0.563	0.305	1.55	0.740	0.128	41.97
7	0.888	0.597	0.291	1.575	0.755	0.133	45.73
8	0.906	0.619	0.287	1.54	0.772	0.134	46.66
9	0.89	0.577	0.313	1.5	0.756	0.134	42.81
10	0.703	0.389	0.314	1.715	0.590	0.113	36.15
11	0.766	0.484	0.282	1.61	0.645	0.121	42.79
12	0.841	0.555	0.286	1.54	0.722	0.119	41.58
13	0.844	0.552	0.292	1.58	0.710	0.134	45.85
14	0.827	0.577	0.25	1.575	0.710	0.117	46.86
15	0.803	0.544	0.259	1.604	0.690	0.113	43.57
16	0.801	0.544	0.257	1.6	0.685	0.116	45.14
17	0.732	0.483	0.249	1.64	0.639	0.093	37.34
18	0.761	0.516	0.245	1.624	0.653	0.108	44.20
19	0.842	0.569	0.273	1.548	0.724	0.118	43.40
20	0.853	0.566	0.287	1.55	0.728	0.125	43.42
21	0.919	0.633	0.286	1.514	0.783	0.136	47.43
22	0.919	0.625	0.294	1.518	0.783	0.136	46.17
23	0.857	0.562	0.295	1.539	0.726	0.131	44.48
24	0.861	0.567	0.294	1.56	0.718	0.143	48.66
25	0.729	0.457	0.272	1.647	0.617	0.112	41.22
26	0.71	0.468	0.242	1.657	0.607	0.103	42.76
27	0.757	0.512	0.245	1.64	0.641	0.116	47.16
28	0.843	0.542	0.301	1.585	0.702	0.141	46.98

Sample No.	e_{max} (Eq.3.6)	e_{min} (Eq.3.8)	e_{max} - e_{min}	$(\gamma_d)_{rs}$	e_{rs} (Eq.3.13)	$e_{max} - e_{rs}$	$(D_r)_{rs}$ (Eq.3.17)
29	0.509	0.235	0.274	1.835	0.410	0.099	36.20
30	0.505	0.273	0.232	1.83	0.415	0.090	38.66
31	0.482	0.229	0.253	1.863	0.390	0.092	36.48
32	0.481	0.243	0.238	1.85	0.398	0.083	34.94
33	0.544	0.256	0.288	1.795	0.440	0.104	36.27
34	0.492	0.233	0.259	1.858	0.395	0.097	37.43
35	0.487	0.249	0.238	1.851	0.399	0.088	37.10
36	0.48	0.268	0.212	1.848	0.398	0.082	38.55
37	0.47	0.225	0.245	1.863	0.384	0.086	35.19
38	0.578	0.356	0.222	1.73	0.488	0.090	40.34
39	0.583	0.278	0.305	1.748	0.477	0.106	34.90
40	0.545	0.315	0.23	1.762	0.462	0.083	36.10
41	0.596	0.303	0.293	1.728	0.494	0.102	34.94
42	0.574	0.308	0.266	1.729	0.478	0.096	35.97
43	0.579	0.301	0.278	1.748	0.482	0.097	35.00
44	0.563	0.297	0.266	1.75	0.471	0.092	34.64
45	0.548	0.292	0.256	1.79	0.456	0.092	35.77
46	0.551	0.346	0.205	1.77	0.469	0.082	39.76
47	0.498	0.297	0.201	1.838	0.424	0.074	36.90
48	0.492	0.261	0.231	1.808	0.414	0.078	33.65
49	0.59	0.302	0.288	1.735	0.479	0.111	38.55
50	0.524	0.288	0.236	1.794	0.435	0.089	37.80
51	0.621	0.331	0.29	1.668	0.521	0.100	34.49
52	0.621	0.335	0.286	1.665	0.523	0.098	34.43
53	0.618	0.341	0.277	1.677	0.523	0.095	34.31
54	0.607	0.33	0.277	1.7	0.508	0.099	35.66
55	0.571	0.284	0.287	1.74	0.469	0.102	35.55

Table 4.8: Experimental Relative Density with reference to Reduced Modified Proctor Test

Sample No.	e_{max} (Eq.3.6)	e_{min} (Eq.3.8)	e_{max} - e_{min}	$(\gamma_d)_{rm}$	e_{rm} (Eq.3.13)	$e_{max} - e_{rm}$	$(D_r)_{rm}$ (Eq.3.18)
1	0.791	0.504	0.287	1.661	0.582	0.209	72.97
2	0.949	0.662	0.287	1.58	0.725	0.224	77.94
3	0.775	0.512	0.263	1.69	0.571	0.204	77.56
4	0.967	0.678	0.289	1.56	0.734	0.233	80.63
5	0.771	0.51	0.261	1.715	0.584	0.187	71.55
6	0.868	0.563	0.305	1.66	0.625	0.243	79.77
7	0.888	0.597	0.291	1.665	0.660	0.228	78.33
8	0.906	0.619	0.287	1.63	0.674	0.232	80.76
9	0.89	0.577	0.313	1.59	0.657	0.233	74.57
10	0.703	0.389	0.314	1.84	0.482	0.221	70.53
11	0.766	0.484	0.282	1.71	0.549	0.217	76.91

Sample No.	e_{max} (Eq.3.6)	e_{min} (Eq.3.8)	e_{max} - e_{min}	$(\gamma_d)_{rm}$	e_{rm} (Eq.3.13)	$e_{max} - e_{rm}$	$(D_r)_{rm}$ (Eq.3.18)
12	0.841	0.555	0.286	1.63	0.627	0.214	74.83
13	0.844	0.552	0.292	1.66	0.628	0.216	74.07
14	0.827	0.577	0.25	1.66	0.622	0.205	81.88
15	0.803	0.544	0.259	1.7	0.595	0.208	80.42
16	0.801	0.544	0.257	1.69	0.595	0.206	80.05
17	0.732	0.483	0.249	1.736	0.548	0.184	73.74
18	0.761	0.516	0.245	1.72	0.560	0.201	81.85
19	0.842	0.569	0.273	1.65	0.617	0.225	82.43
20	0.853	0.566	0.287	1.66	0.614	0.239	83.33
21	0.919	0.633	0.286	1.611	0.676	0.243	84.97
22	0.919	0.625	0.294	1.62	0.671	0.248	84.36
23	0.857	0.562	0.295	1.65	0.610	0.247	83.83
24	0.861	0.567	0.294	1.66	0.614	0.247	83.86
25	0.729	0.457	0.272	1.76	0.513	0.216	79.39
26	0.71	0.468	0.242	1.764	0.509	0.201	83.03
27	0.757	0.512	0.245	1.73	0.556	0.201	82.01
28	0.843	0.542	0.301	1.69	0.596	0.247	82.11
29	0.509	0.235	0.274	1.98	0.307	0.202	73.88
30	0.505	0.273	0.232	1.947	0.330	0.175	75.32
31	0.482	0.229	0.253	1.99	0.301	0.181	71.54
32	0.481	0.243	0.238	1.98	0.306	0.175	73.50
33	0.544	0.256	0.288	1.94	0.332	0.212	73.63
34	0.492	0.233	0.259	1.99	0.303	0.189	73.16
35	0.487	0.249	0.238	1.969	0.315	0.172	72.32
36	0.48	0.268	0.212	1.95	0.325	0.155	73.05
37	0.47	0.225	0.245	1.99	0.295	0.175	71.23
38	0.578	0.356	0.222	1.83	0.407	0.171	76.98
39	0.583	0.278	0.305	1.89	0.366	0.217	71.28
40	0.545	0.315	0.23	1.86	0.385	0.160	69.59
41	0.596	0.303	0.293	1.86	0.388	0.208	71.11
42	0.574	0.308	0.266	1.84	0.389	0.185	69.50
43	0.579	0.301	0.278	1.865	0.389	0.190	68.44
44	0.563	0.297	0.266	1.876	0.372	0.191	71.78
45	0.548	0.292	0.256	1.91	0.365	0.183	71.52
46	0.551	0.346	0.205	1.86	0.398	0.153	74.45
47	0.498	0.297	0.201	1.94	0.349	0.149	74.14
48	0.492	0.261	0.231	1.92	0.332	0.160	69.36
49	0.59	0.302	0.288	1.853	0.385	0.205	71.26
50	0.524	0.288	0.236	1.916	0.343	0.181	76.52
51	0.621	0.331	0.29	1.78	0.425	0.196	67.49
52	0.621	0.335	0.286	1.772	0.431	0.190	66.58
53	0.618	0.341	0.277	1.79	0.427	0.191	69.02
54	0.607	0.33	0.277	1.81	0.417	0.190	68.75
55	0.571	0.284	0.287	1.86	0.374	0.197	68.57

4.3.1 Prediction of void ratio corresponding to reduced standard Proctor test (e_{rs}) from mean grain size (D_{50})

The void ratio corresponding to reduced standard Proctor test (e_{rs}) of 55 samples has been plotted against their corresponding mean grain size (D_{50}). Several equations have been tried to fit to these experimental data. However, the best fit line to these sets of data is shown in Figure 4.13.

$$e_{rs} = 0.5039 \ D_{50}^{-0.327} \tag{4.15}$$

$$r^2 = 0.78$$

The least square value is comparatively good than other set of equations. For the sake of space and brevity other equations are not shown here.

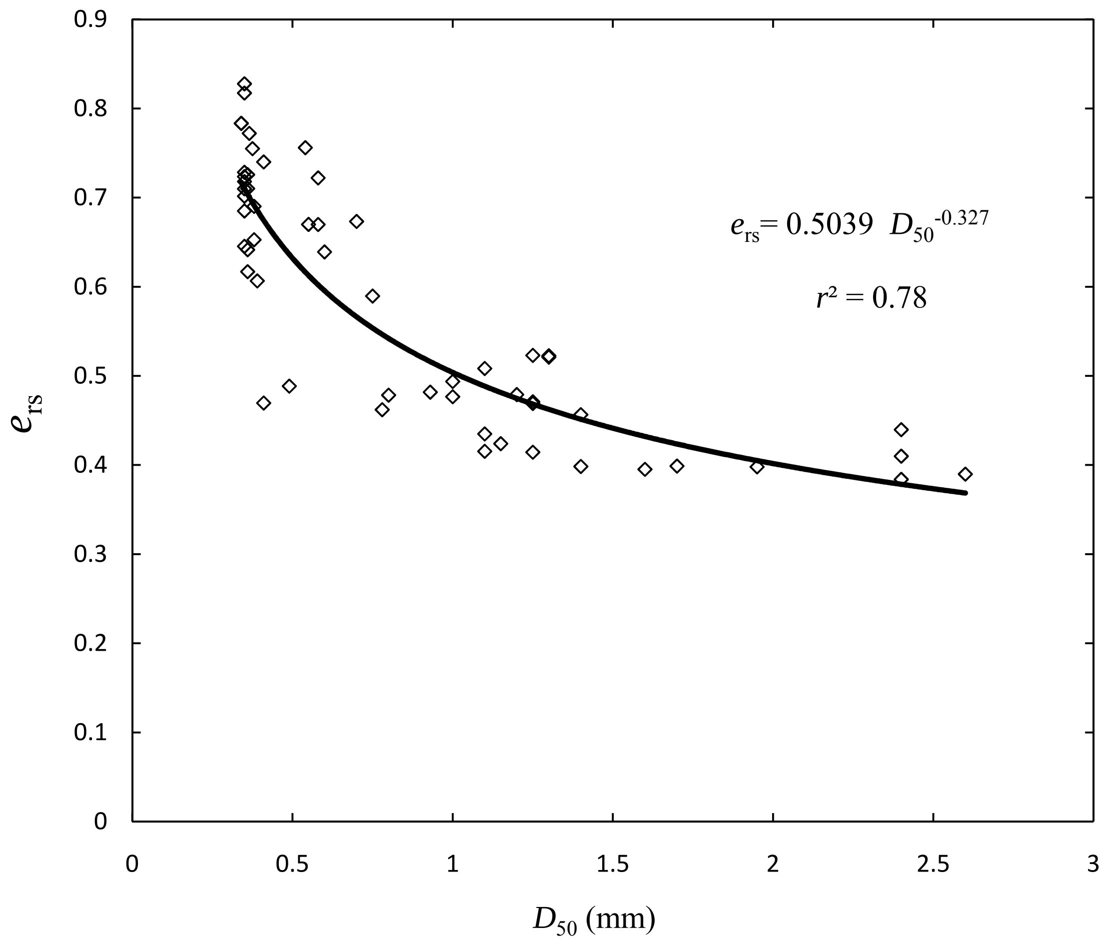


Figure 4.13: Variation of e_{rs} with D_{50}

4.3.2 Prediction of void ratio corresponding to reduced modified Proctor test (e_{rm}) from mean grain size (D_{50})

The void ratio corresponding to reduced modified Proctor test (e_{rm}) of 55 samples has been plotted against their corresponding mean grain size (D_{50}). Several equations have been tried to fit to these experimental data. However, the best fit line to these sets of data is shown in Figure 4.14.

$$e_{rm} = 0.4087\ D_{50}^{\ -0.389} \tag{4.16}$$

$$r^2 = 0.81$$

The least square value is comparatively good than other set of equations. For the sake of space and brevity other equations are not shown here.

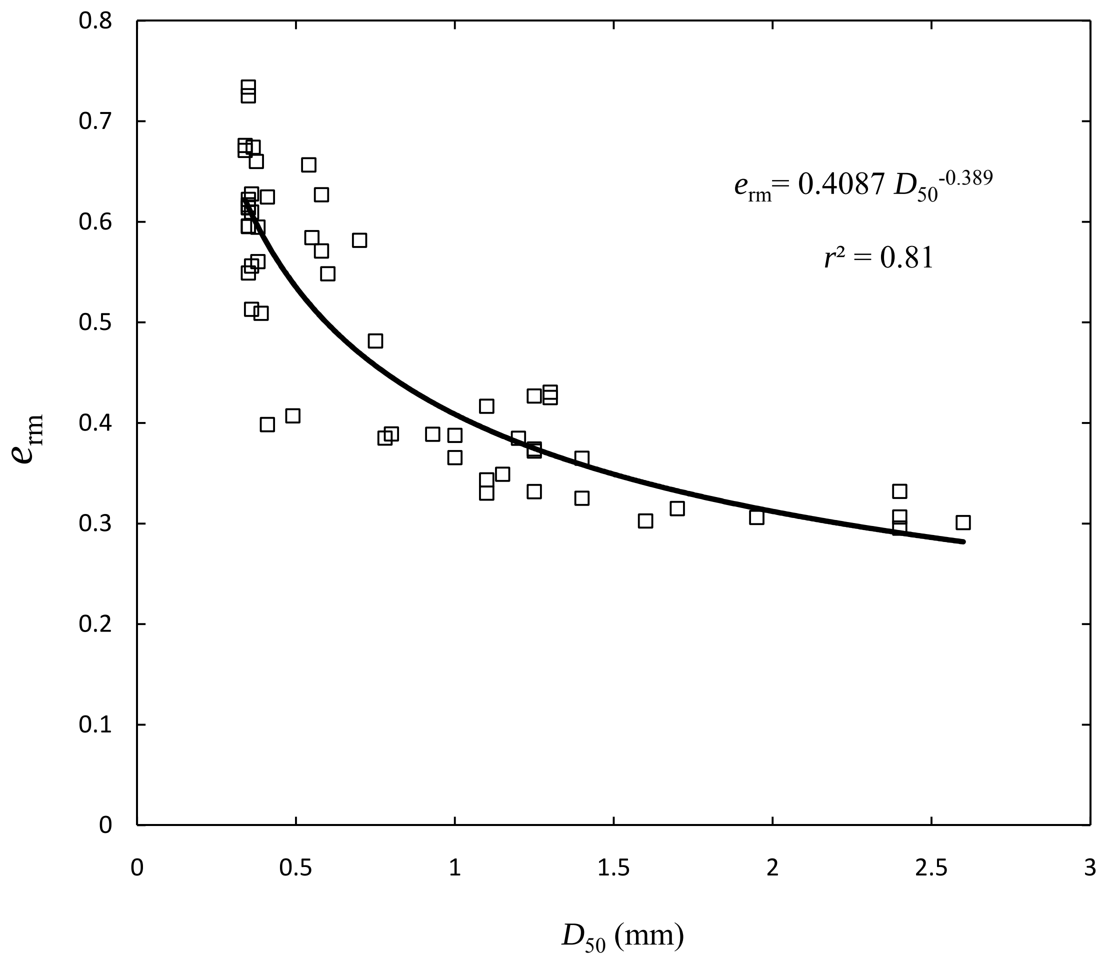


Figure 4.14: Variation of e_{rm} with D_{50}

4.3.3 Prediction of Relative Density (D_r)

The void ratios like e_{max}, e_{min}, e_{rs} and e_{rm} are empirically correlated with D_{50}. From the empirical relations of e_{max}, e_{min}, e_{rs} and e_{rm} as obtained earlier (Eq. 4.1, 4.2, 4.15, and 4.16) has been utilized to predict the relative density of sand from D_{50} as follows:

Relative density corresponding to reduced standard Proctor test, $(D_r)_{rs}$

$$(D_r)_{rs} = \frac{e_{\max} - e_{rs}}{e_{\max} - e_{\min}} \times 100 = \frac{0.6042\ D_{50}^{-0.304} - 0.5039\ D_{50}^{-0.327}}{0.6042\ D_{50}^{-0.304} - 0.3346\ D_{50}^{-0.491}} \times 100 \tag{4.17}$$

where

$$e_{\max} = 0.6042\ D_{50}^{-0.304}$$
$$e_{\min} = 0.3346\ D_{50}^{-0.491}$$
$$e_{rs} = 0.5039\ D_{50}^{-0.327}$$

Relative density corresponding to reduced modified Proctor test, $(D_r)_{rm}$

$$(D_r)_{rm} = \frac{e_{\max} - e_{rm}}{e_{\max} - e_{\min}} \times 100 = \frac{0.6042\ D_{50}^{-0.304} - 0.4087\ D_{50}^{-0.389}}{0.6042\ D_{50}^{-0.304} - 0.3346\ D_{50}^{-0.491}} \times 100 \tag{4.18}$$

where

$$e_{\max} = 0.6042\ D_{50}^{-0.304}$$
$$e_{\min} = 0.3346\ D_{50}^{-0.491}$$
$$e_{rm} = 0.4087\ D_{50}^{-0.389}$$

The relative density predicted by conducting Reduced Standard and Reduced Modified Proctor tests by using Eq. (4.17, 4.18) are shown in Table 4.9 and Table 4.10 respectively.

Table 4.9: Predicted Relative Density with reference to Reduced Standard Proctor Test

Sample No.	**Predicted e_{max}**	**Predicted e_{min}**	**Predicted e_{max} - e_{min}**	**Predicted e_{rs}**	**Predicted e_{max} - e_{rs}**	**Predicted $(D_r)_{rs}$ (%)**
1	0.673	0.399	0.275	0.566	0.107	39.00
2	0.831	0.560	0.271	0.710	0.121	44.66
3	0.713	0.437	0.276	0.602	0.111	40.20
4	0.831	0.560	0.271	0.710	0.121	44.66
5	0.725	0.449	0.276	0.613	0.112	40.57
6	0.792	0.518	0.274	0.674	0.118	43.02
7	0.814	0.542	0.272	0.694	0.120	43.91
8	0.821	0.549	0.272	0.701	0.120	44.20
9	0.729	0.453	0.276	0.616	0.112	40.71
10	0.659	0.385	0.274	0.554	0.106	38.61
11	0.831	0.560	0.271	0.710	0.121	44.66
12	0.713	0.437	0.276	0.602	0.111	40.20
13	0.824	0.553	0.272	0.704	0.120	44.35
14	0.831	0.560	0.271	0.710	0.121	44.66
15	0.811	0.538	0.273	0.691	0.119	43.77
16	0.831	0.560	0.271	0.710	0.121	44.66
17	0.706	0.430	0.276	0.596	0.110	39.97
18	0.811	0.538	0.273	0.691	0.119	43.77
19	0.831	0.560	0.271	0.710	0.121	44.66
20	0.831	0.560	0.271	0.710	0.121	44.66
21	0.839	0.568	0.270	0.717	0.122	44.99
22	0.839	0.568	0.270	0.717	0.122	44.99
23	0.824	0.553	0.272	0.704	0.120	44.35
24	0.831	0.560	0.271	0.710	0.121	44.66
25	0.824	0.553	0.272	0.704	0.120	44.35
26	0.804	0.531	0.273	0.686	0.119	43.51
27	0.824	0.553	0.272	0.704	0.120	44.35
28	0.831	0.560	0.271	0.710	0.121	44.66
29	0.463	0.218	0.245	0.378	0.085	34.47
30	0.587	0.319	0.268	0.488	0.099	36.81
31	0.452	0.209	0.243	0.369	0.083	34.30
32	0.493	0.241	0.252	0.405	0.088	34.96
33	0.463	0.218	0.245	0.378	0.085	34.47
34	0.524	0.266	0.258	0.432	0.092	35.51
35	0.514	0.258	0.256	0.424	0.091	35.33
36	0.545	0.284	0.262	0.451	0.094	35.93
37	0.463	0.218	0.245	0.378	0.085	34.47
38	0.751	0.475	0.276	0.636	0.114	41.45

Sample No.	Predicted e_{max}	Predicted e_{min}	Predicted e_{max} - e_{min}	Predicted e_{rs}	Predicted e_{max} - e_{rs}	Predicted $(D_r)_{rs}$ (%)
39	0.604	0.335	0.270	0.504	0.100	37.20
40	0.652	0.378	0.274	0.547	0.105	38.40
41	0.604	0.335	0.270	0.504	0.100	37.20
42	0.647	0.373	0.273	0.542	0.105	38.27
43	0.618	0.347	0.271	0.516	0.102	37.53
44	0.565	0.300	0.265	0.468	0.096	36.32
45	0.545	0.284	0.262	0.451	0.094	35.93
46	0.792	0.518	0.274	0.674	0.118	43.02
47	0.579	0.312	0.267	0.481	0.098	36.63
48	0.565	0.300	0.265	0.468	0.096	36.32
49	0.572	0.306	0.266	0.475	0.097	36.47
50	0.587	0.319	0.268	0.488	0.099	36.81
51	0.558	0.294	0.264	0.462	0.095	36.18
52	0.558	0.294	0.264	0.462	0.095	36.18
53	0.565	0.300	0.265	0.468	0.096	36.32
54	0.587	0.319	0.268	0.488	0.099	36.81
55	0.565	0.300	0.265	0.468	0.096	36.32

Table 4.10: Predicted Relative Density with reference to Reduced Modified Proctor Test

Sample No.	Predicted e_{max}	Predicted e_{min}	Predicted e_{max} - e_{min}	Predicted e_{rm}	Predicted e_{max} - e_{rm}	Predicted $(D_r)_{rm}$ (%)
1	0.673	0.399	0.275	0.470	0.204	74.20
2	0.831	0.560	0.271	0.615	0.217	79.87
3	0.713	0.437	0.276	0.505	0.208	75.36
4	0.831	0.560	0.271	0.615	0.217	79.87
5	0.725	0.449	0.276	0.516	0.209	75.73
6	0.792	0.518	0.274	0.578	0.214	78.19
7	0.814	0.542	0.272	0.599	0.216	79.10
8	0.821	0.549	0.272	0.605	0.216	79.39
9	0.729	0.453	0.276	0.519	0.209	75.86
10	0.659	0.385	0.274	0.457	0.202	73.83
11	0.831	0.560	0.271	0.615	0.217	79.87
12	0.713	0.437	0.276	0.505	0.208	75.36
13	0.824	0.553	0.272	0.608	0.216	79.54
14	0.831	0.560	0.271	0.615	0.217	79.87
15	0.811	0.538	0.273	0.595	0.215	78.96
16	0.831	0.560	0.271	0.615	0.217	79.87
17	0.706	0.430	0.276	0.499	0.207	75.13
18	0.811	0.538	0.273	0.595	0.215	78.96

Sample No.	Predicted e_{max}	Predicted e_{min}	Predicted e_{max} - e_{min}	Predicted e_{rs}	Predicted e_{max} - e_{rs}	Predicted $(D_r)_{rs}$ (%)
19	0.831	0.560	0.271	0.615	0.217	79.87
20	0.831	0.560	0.271	0.615	0.217	79.87
21	0.839	0.568	0.270	0.622	0.217	80.21
22	0.839	0.568	0.270	0.622	0.217	80.21
23	0.824	0.553	0.272	0.608	0.216	79.54
24	0.831	0.560	0.271	0.615	0.217	79.87
25	0.824	0.553	0.272	0.608	0.216	79.54
26	0.804	0.531	0.273	0.589	0.215	78.69
27	0.824	0.553	0.272	0.608	0.216	79.54
28	0.831	0.560	0.271	0.615	0.217	79.87
29	0.463	0.218	0.245	0.291	0.172	70.22
30	0.587	0.319	0.268	0.394	0.193	72.16
31	0.452	0.209	0.243	0.282	0.170	70.10
32	0.493	0.241	0.252	0.315	0.178	70.59
33	0.463	0.218	0.245	0.291	0.172	70.22
34	0.524	0.266	0.258	0.340	0.183	71.03
35	0.514	0.258	0.256	0.332	0.182	70.89
36	0.545	0.284	0.262	0.359	0.187	71.39
37	0.463	0.218	0.245	0.291	0.172	70.22
38	0.751	0.475	0.276	0.539	0.211	76.61
39	0.604	0.335	0.270	0.409	0.196	72.51
40	0.652	0.378	0.274	0.450	0.201	73.62
41	0.604	0.335	0.270	0.409	0.196	72.51
42	0.647	0.373	0.273	0.446	0.201	73.50
43	0.618	0.347	0.271	0.420	0.197	72.81
44	0.565	0.300	0.265	0.375	0.190	71.72
45	0.545	0.284	0.262	0.359	0.187	71.39
46	0.792	0.518	0.274	0.578	0.214	78.19
47	0.579	0.312	0.267	0.387	0.192	72.00
48	0.565	0.300	0.265	0.375	0.190	71.72
49	0.572	0.306	0.266	0.381	0.191	71.86
50	0.587	0.319	0.268	0.394	0.193	72.16
51	0.558	0.294	0.264	0.369	0.189	71.60
52	0.558	0.294	0.264	0.369	0.189	71.60
53	0.565	0.300	0.265	0.375	0.190	71.72
54	0.587	0.319	0.268	0.394	0.193	72.16
55	0.565	0.300	0.265	0.375	0.190	71.72

4.3.4 Comparison of predicted relative density with experimental values

The values of relative density obtained from the experimental Reduced Standard and Reduced Modified Proctor tests have been plotted against the predicted values obtained as a function of D_{50} are shown in Figure 4.15. The same has been presented in Table 4.11 for better comparison.

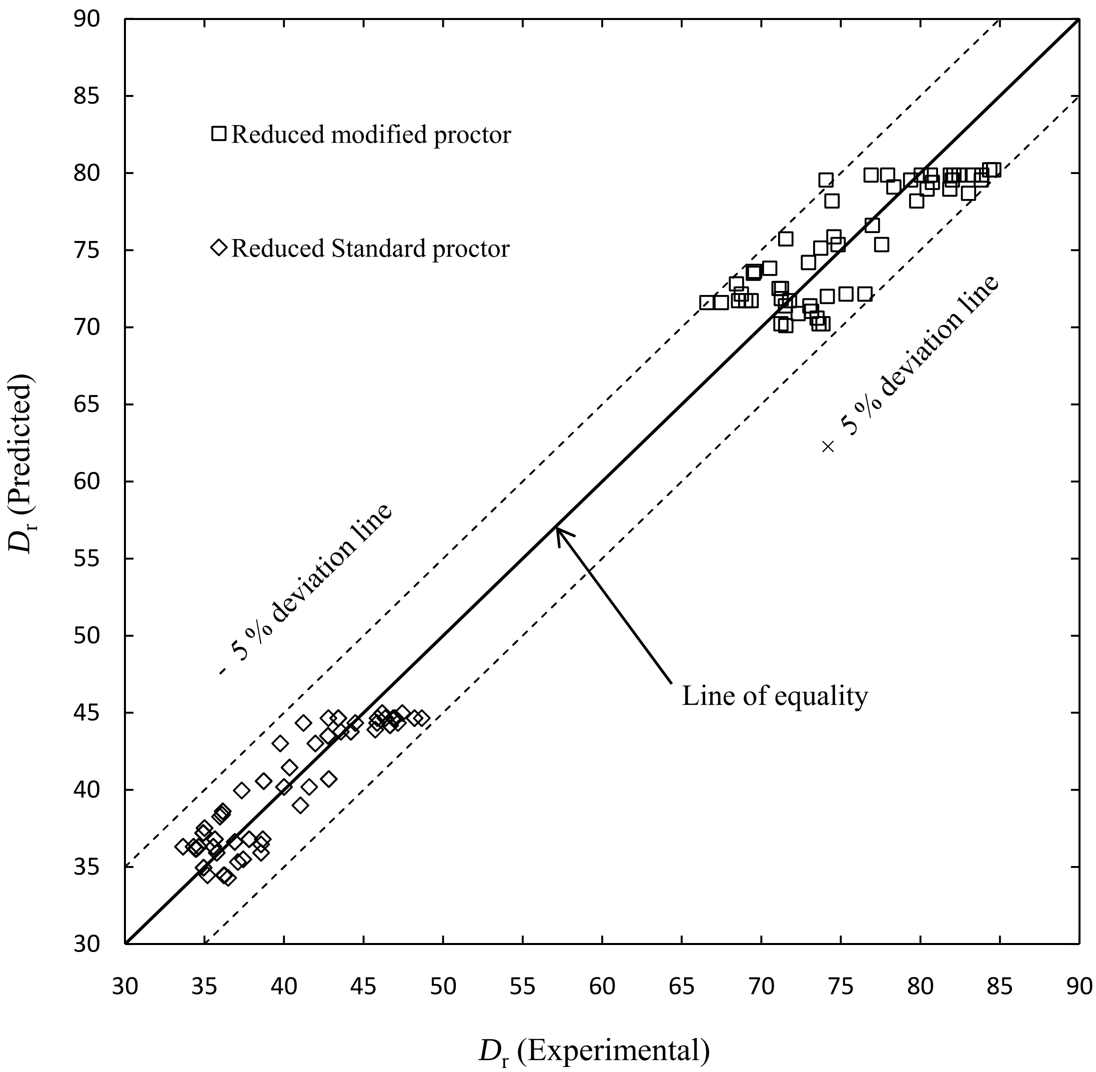


Figure 4.15: Plot of D_r (experimental) versus D_r (predicted)

Table 4.11: Percentage deviation between predicted and experimental relative density values

Sample No.	Reduced Standard Proctor Test			Reduced Modified Proctor Test		
	Predicted D_r	**Experimental D_r**	**% Deviation**	**Predicted D_r**	**Experimental D_r**	**% Deviation**
1	39.00	41.03	5.194	74.20	72.97	-1.659
2	44.66	45.88	2.728	79.87	77.94	-2.414
3	40.20	40.00	-0.501	75.36	77.56	2.925
4	44.66	48.20	7.930	79.87	80.63	0.958
5	40.57	38.72	-4.568	75.73	71.54	-5.532
6	43.02	41.97	-2.442	78.19	79.77	2.027
7	43.91	45.73	4.148	79.10	78.33	-0.971
8	44.20	46.66	5.579	79.39	80.76	1.718
9	40.71	42.81	5.173	75.86	74.57	-1.707
10	38.61	36.15	-6.387	73.83	70.53	-4.465
11	44.66	42.79	-4.191	79.87	76.91	-3.706
12	40.20	41.58	3.444	75.36	74.83	-0.707
13	44.35	45.85	3.385	79.54	74.07	-6.881
14	44.66	46.86	4.939	79.87	81.88	2.527
15	43.77	43.57	-0.459	78.96	80.42	1.857
16	44.66	46.36	3.819	79.87	80.05	0.233
17	39.97	37.34	-6.574	75.13	73.74	-1.856
18	43.77	44.20	0.978	78.96	81.85	3.666
19	44.66	43.40	-2.814	79.87	82.43	3.208
20	44.66	43.42	-2.773	79.87	83.33	4.331
21	44.99	47.43	5.423	80.21	84.61	5.486
22	44.99	46.17	2.620	80.21	84.36	5.173
23	44.35	44.48	0.292	79.54	83.83	5.388
24	44.66	48.66	8.954	79.87	83.86	4.997
25	44.35	41.22	-7.049	79.54	79.39	-0.200
26	43.51	42.76	-1.716	78.69	83.03	5.519
27	44.35	47.16	6.339	79.54	82.01	3.102
28	44.66	46.98	5.210	79.87	82.11	2.805
29	34.47	36.20	5.022	70.22	73.88	5.207
30	36.81	38.66	5.046	72.16	75.32	4.388
31	34.30	36.48	6.366	70.10	71.54	2.047
32	34.96	34.94	-0.047	70.59	73.50	4.120
33	34.47	36.27	5.211	70.22	73.63	4.842
34	35.51	37.43	5.430	71.03	73.16	2.994
35	35.33	37.10	5.011	70.89	72.32	2.017
36	35.93	38.55	7.312	71.39	73.05	2.333
37	34.47	35.19	2.083	70.22	71.23	1.436
38	41.45	40.34	-2.680	76.61	76.98	0.488
39	37.20	34.90	-6.183	72.51	71.28	-1.710

Sample No.	Reduced Standard Proctor Test			Reduced Modified Proctor Test		
	Predicted D_r	**Experimental D_r**	**% Deviation**	**Predicted D_r**	**Experimental D_r**	**% Deviation**
40	38.40	36.10	-5.994	73.62	69.59	-5.483
41	37.20	34.94	-6.092	72.51	71.11	-1.932
42	38.27	35.97	-5.990	73.50	69.50	-5.442
43	37.53	35.00	-6.729	72.81	68.44	-6.007
44	36.32	34.64	-4.620	71.72	71.78	0.074
45	35.93	35.77	-0.429	71.39	71.52	0.180
46	43.02	39.76	-7.572	78.19	74.45	-4.784
47	36.63	36.90	0.736	72.00	74.15	2.985
48	36.32	33.65	-7.349	71.72	69.36	-3.293
49	36.47	38.55	5.719	71.86	71.26	-0.836
50	36.81	37.80	2.710	72.16	76.52	6.041
51	36.18	34.49	-4.671	71.60	67.49	-5.746
52	36.18	34.43	-4.826	71.60	66.58	-7.018
53	36.32	34.31	-5.526	71.72	69.02	-3.773
54	36.81	35.66	-3.126	72.16	68.75	-4.727
55	36.32	35.55	-2.109	71.72	68.57	-4.395

4.4 SUMMARY OF RESULTS CONSIDERING ALLTHE ENERGY LEVEL OF COMPACTION

4.4.1 Comparison of void ratios (e_{max}, e_{min}, e_s e_m, e_{rs} e_{rm})

The void ratios (e_{max}, e_{min}, e_s, e_m, e_{rs}, and e_{rm}) corresponding to different compaction energy of 55 samples as predicted earlier with respect to mean diameter of grains have been plotted against their corresponding mean grain size (D_{50}) as shown in Figure 4.16.

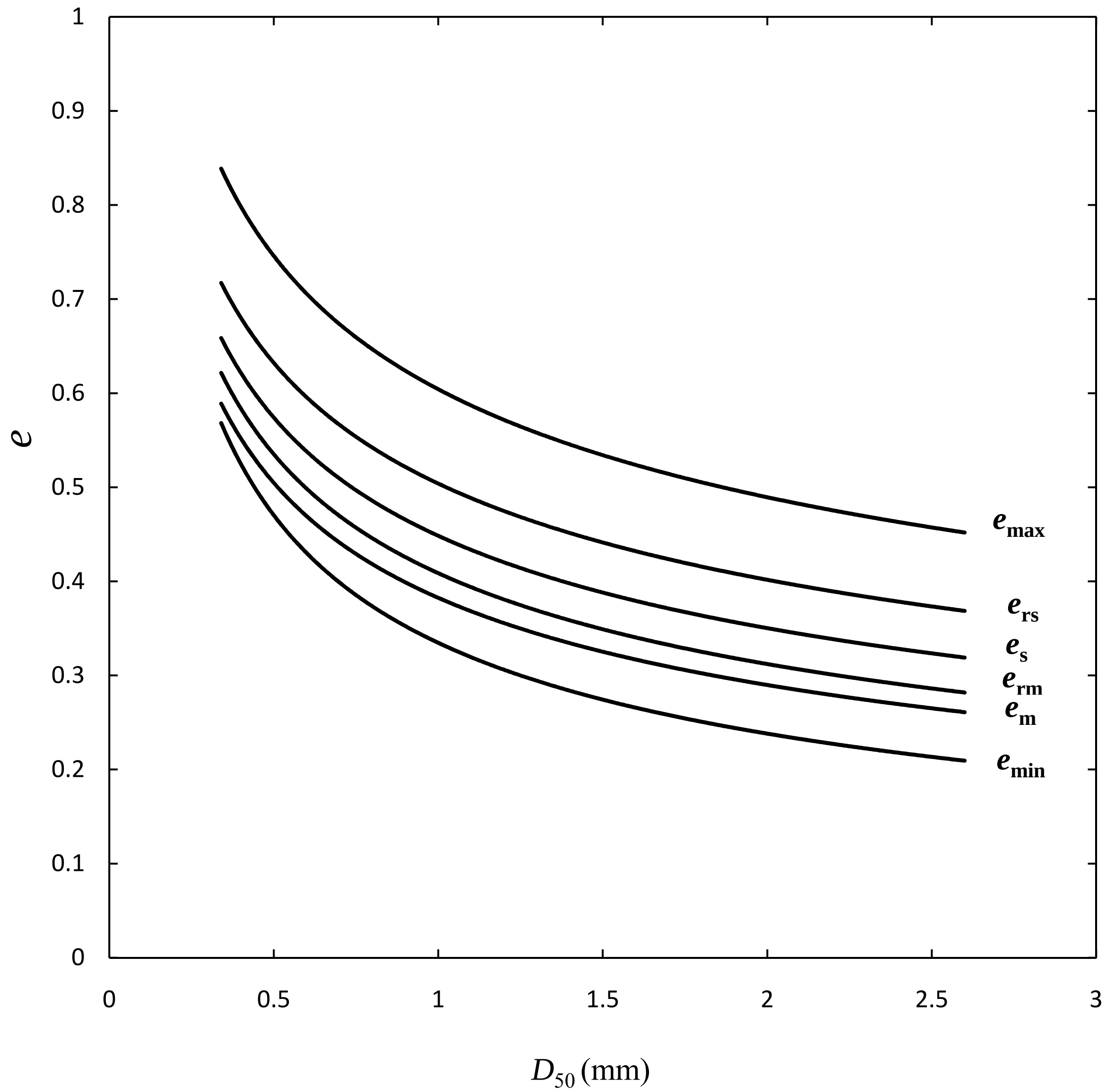


Figure 4.16: Plot of void ratio (e_{max}, e_{min}, e_s e_m, e_{rs} e_{rm}) versus D_{50}

4.4.2 Empirical equations for void ratios (e_{max}, e_{min}, e_s e_m, e_{rs} e_{rm}) at particular energy levels

Based on the test results, correlation of voids ratio (e), compaction energy (E) and mean grain size (D_{50}) have been made. The equation for the void ratios at six energy levels of compaction (E) done in the laboratory i.e. 356 kNm/m^3, 593 kN-m/m^3, 1295 kN-m/m^3, 2698 kN-m/m^3 loosest state, and densest state can be expressed in the form as below:

$$e = a\, D_{50}^{\;-b} \tag{4.19}$$

where, e = void ratio at a particular energy level

a = a constant for a particular energy level

b = a constant for a particular energy level

The values of coefficient "a" and "b" have been presented in Table 4.12 for different energy levels under consideration. At any particular energy level under consideration, the void ratio can be correlated with the mean diameter of grains by the equation 4.19 and Table 4.12.

Table 4.12: Coefficient "a" and "b" values for different energy levels

Energy Level	Void ratio	a	b
Minimum	e_{max}	0.6042	0.304
356 kN-m/m^3	e_{rs}	0.5039	0.327
593 kN-m/m^3	e_s	0.4484	0.356
1295 kN-m/m^3	e_{rm}	0.4087	0.389
2698 kN-m/m^3	e_m	0.3825	0.400
Maximum	e_{min}	0.3346	0.491

The empirical equations developed for a particular energy level are as follows.

$$e_{max} = 0.6042\, D_{50}^{\;-0.304} \qquad r^2 = 0.76 \tag{4.20}$$

$$e_{rs} = 0.5039\, D_{50}^{\;-0.327} \qquad r^2 = 0.78 \tag{4.21}$$

$$e_s = 0.4484\, D_{50}^{-0.356} \qquad r^2 = 0.80 \tag{4.22}$$

$$e_{rm} = 0.4087\, D_{50}^{-0.389} \qquad r^2 = 0.81 \tag{4.23}$$

$$e_m = 0.3825\, D_{50}^{-0.4} \qquad r^2 = 0.81 \tag{4.24}$$

$$e_{min} = 0.3346\, D_{50}^{-0.491} \qquad r^2 = 0.85 \tag{4.25}$$

4.4.3 Empirical equations for relative density (D_r) at particular energy levels

The relative density at particular energy of compaction such as reduced standard, standard, reduced modified and modified compaction can be correlated with a single parameter like the mean diameter of grains by the following equations:

Relative density for 356 kN-m/m^3 energy level

$$(D_r)_{rs} = \frac{e_{max} - e_{rs}}{e_{max} - e_{min}} \times 100 = \frac{0.6042\, D_{50}^{-0.304} - 0.5039\, D_{50}^{-0.327}}{0.6042\, D_{50}^{-0.304} - 0.3346\, D_{50}^{-0.491}} \times 100 \tag{4.26}$$

Relative density for 593 kN-m/m^3 energy level

$$(D_r)_s = \frac{e_{max} - e_s}{e_{max} - e_{min}} \times 100 = \frac{0.6042\, D_{50}^{-0.304} - 0.4484\, D_{50}^{-0.356}}{0.6042\, D_{50}^{-0.304} - 0.3346\, D_{50}^{-0.491}} \times 100 \tag{4.27}$$

Relative density for 1295 kN-m/m^3 energy level

$$(D_r)_{rm} = \frac{e_{max} - e_{rm}}{e_{max} - e_{min}} \times 100 = \frac{0.6042\, D_{50}^{-0.304} - 0.4087\, D_{50}^{-0.389}}{0.6042\, D_{50}^{-0.304} - 0.3346\, D_{50}^{-0.491}} \times 100 \tag{4.28}$$

Relative density for 2698 kN-m/m^3 energy level

$$(D_r)_m = \frac{e_{max} - e_m}{e_{max} - e_{min}} \times 100 = \frac{0.6042\, D_{50}^{-0.304} - 0.3825\, D_{50}^{-0.4}}{0.6042\, D_{50}^{-0.304} - 0.3346\, D_{50}^{-0.491}} \times 100 \tag{4.29}$$

4.4.4 Comparison of predicted relative density with experimental values at different energy levels

The experimental values of relative density obtained from laboratory reduced standard, standard, reduced modified and modified Proctor tests have been plotted against the predicted values obtained as a function of D_{50} are shown in Figure 4.17.The closeness of the points to the equality line and the inclusion of most of the points within the confidence interval serve only to indicate the validity of the derived emprical equations.

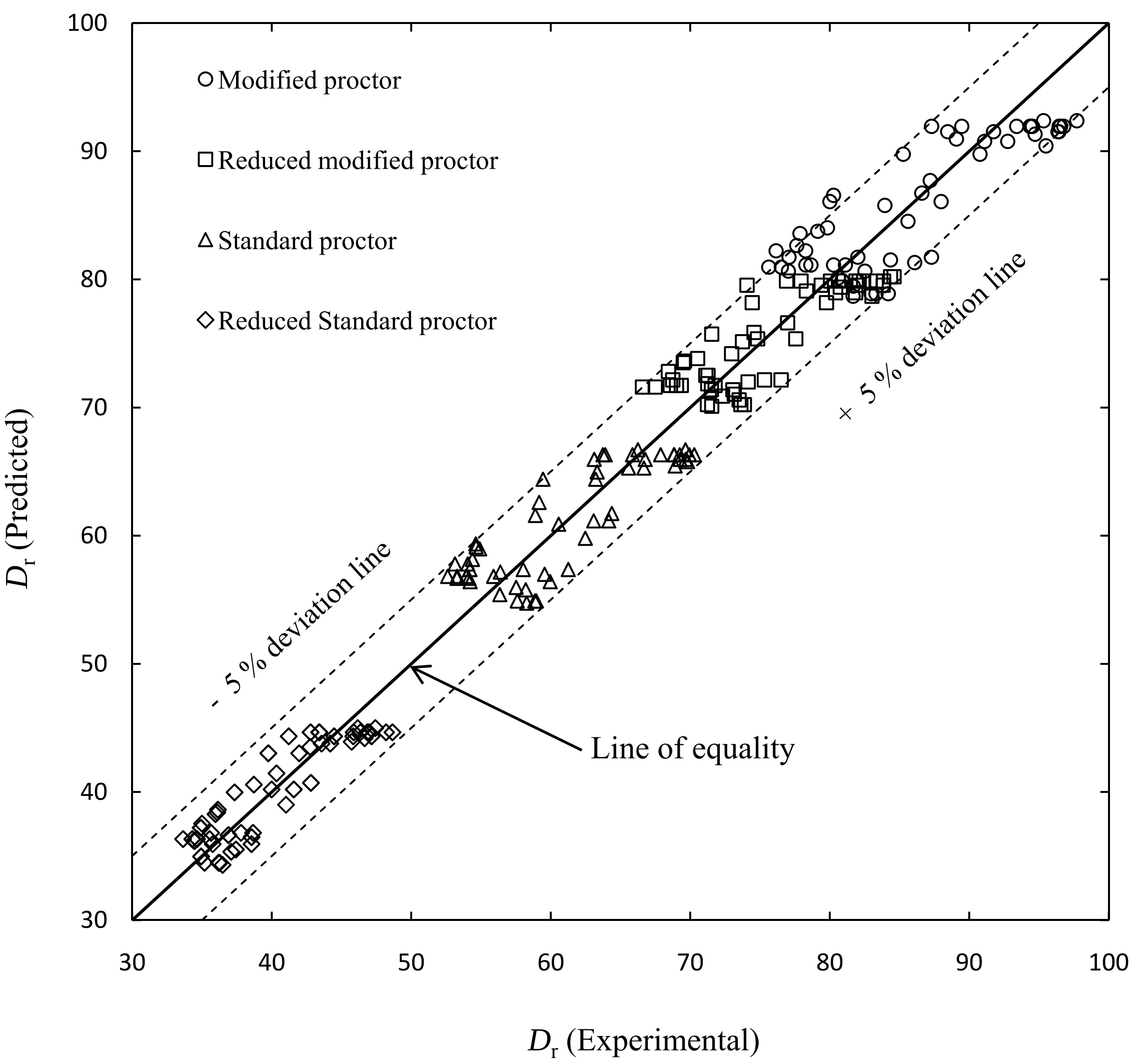


Figure 4.17: Plot of D_r (experimental) versus D_r (predicted) for 356 kNm/m^3, 593 kN-m/m^3, 1295 kN-m/m^3 & 2698 kN-m/m^3

4.4.5 Establishing relationship between relative density (D_r) with mean grain size (D_{50}) at different energy levels

The predicted relative density (D_r) corresponding to different compaction energy of 55 samples have been plotted against their corresponding mean grain size (D_{50}) in the Figure 4.18.

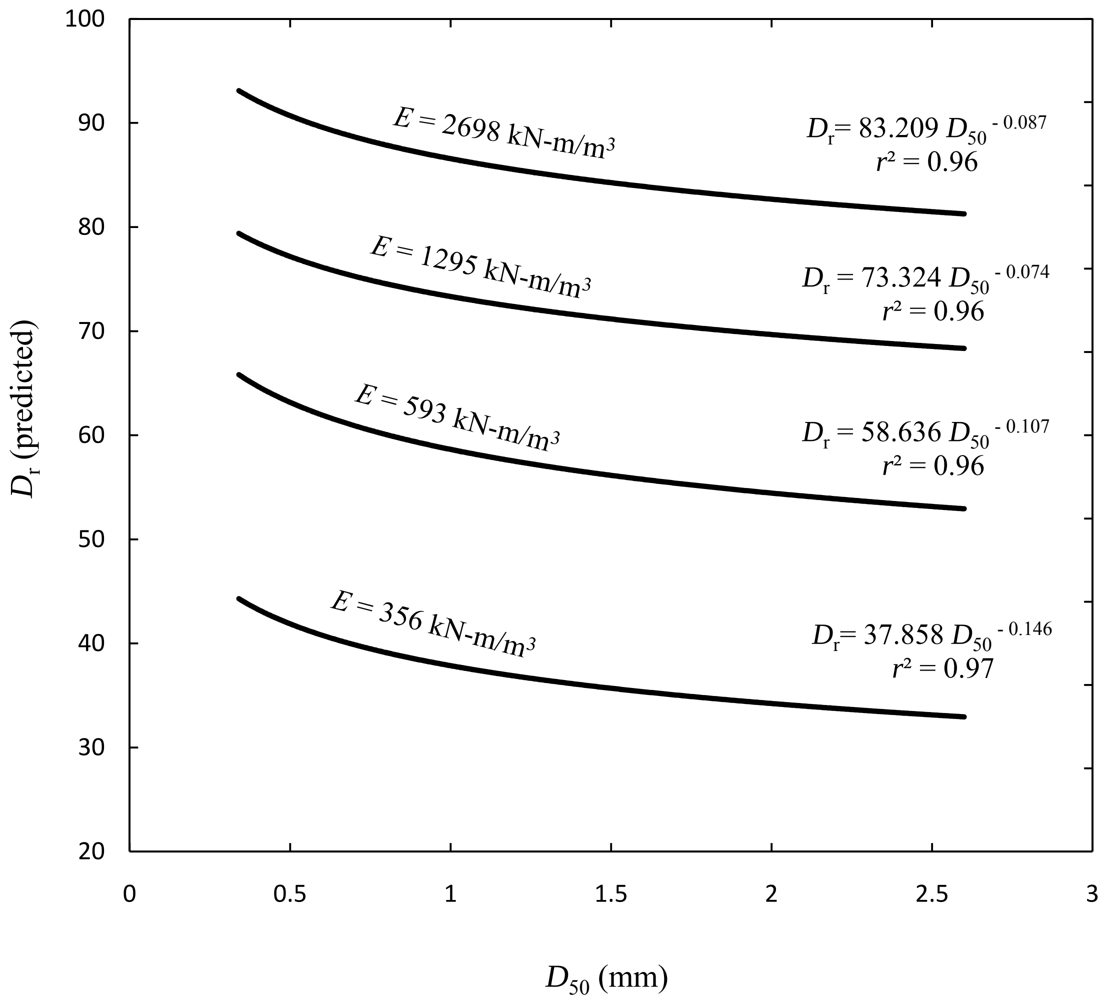


Figure 4.18: Plot of D_r (Predicted) versus D_{50}

The final best-fit models obtained is,

$$D_r = p\ D_{50}^{-q} \tag{4.30}$$

where D_r= relative density at a particular energy level

p = a constant for a particular energy level

q = a constant for a particular energy level

The values of coefficient "a" and "b" have been presented in Table 4.12 for different energy levels.

Table 4.13: Coefficient "p" and "q" values for different energy levels

Energy Level	**p**	**q**
356 kN-m/m^3	83.209	0.087
593 kN-m/m^3	73.324	0.074
1295 kN-m/m^3	58.636	0.107
2698 kN-m/m^3	37.585	0.146

The empirical equations developed at particular compaction energy are,

$$(D_r)_{356kN-m/m^3} = 83.209\ D_{50}^{-0.087} \qquad r^2 = 0.96 \tag{4.31}$$

$$(D_r)_{593kN-m/m^3} = 73.324\ D_{50}^{-0.074} \qquad r^2 = 0.95 \tag{4.32}$$

$$(D_r)_{1295kN-m/m^3} = 58.636\ D_{50}^{-0.107} \qquad r^2 = 0.96 \tag{4.33}$$

$$(D_r)_{2698kN-m/m^3} = 37.585\ D_{50}^{-0.146} \qquad r^2 = 0.97 \tag{4.34}$$

CHAPTER 5

CONCLUSION

CONCLUSION

Laboratory test on 55 samples collected from river bed of Orissa have been carried out for determining relative density at a particular compaction energy corresponding to the standard, modified, reduced standard, reduced modified Proctor compaction tests. The void ratios at different energy levels have been calculated from dry density obtained in the laboratory. From the laboratory tests, the equations for void ratios at such particular energy levels have been predicted by correlating with mean grain size. Relative densities at such energy levels have been predicted by using the equations of void ratios which are function of mean grain size. The following are generalized conclusions from the present work:

1. The most significant variable influencing void ratio is the mean grain size.

2. Predicted relative densities and experimental relative densities at particular energy level are within $\pm$ 5 %.

3. The relative densities at particular energy level can be correlated by empirical equations in terms of mean grain size.

4. This will be helpful for the design specifications in the field since the relative density at particular energy level is correlated with a single parameter such as mean grain size.

CHAPTER 6

SCOPE FOR FURTHER STUDY

SCOPE OF FURTHER STUDY

It is necessary to investigate the effect of angularity and particle shape on the maximum and minimum void ratio and hence on the relative density of sand. It is recommended to derive empirical equations of relative densities at any energy level of compaction. Correlation can be done by considering both vibration as well as impact force while determining the relative density in laboratory simulating to field conditions.

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Appendix A

FIGURES

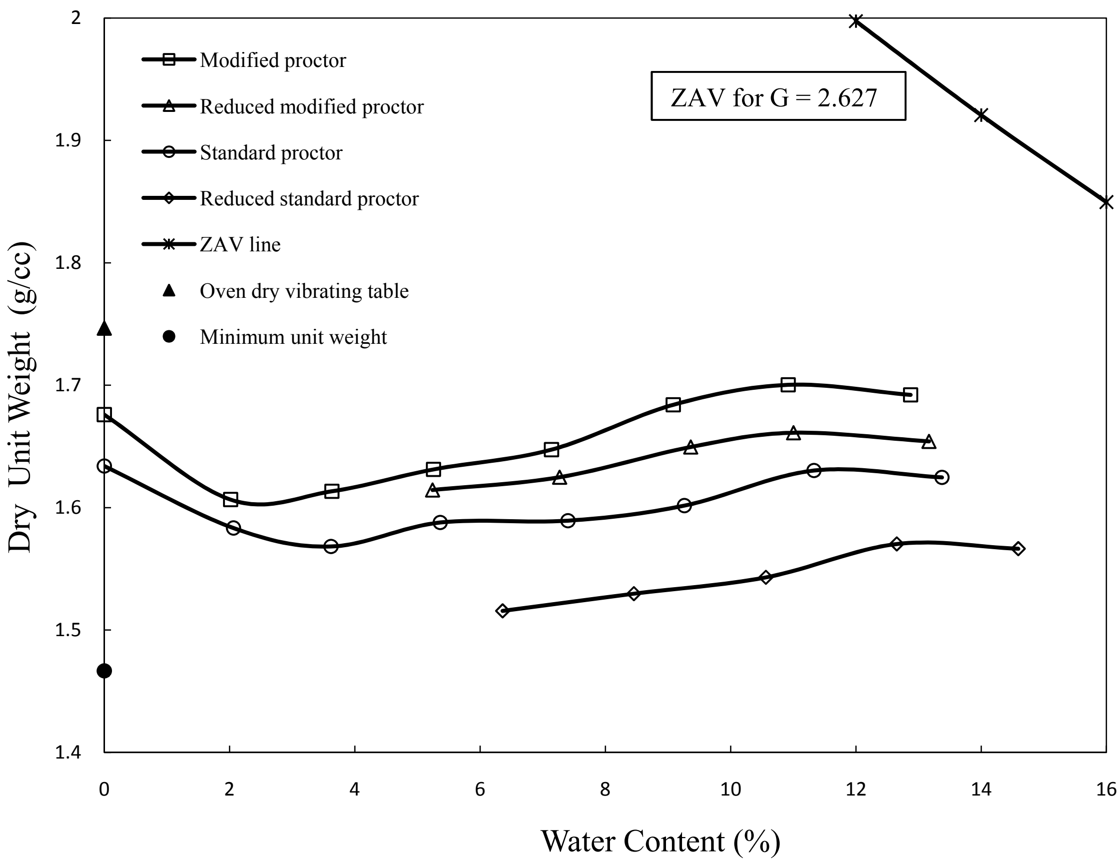

Figure A-1: Compaction results of Sample - 1

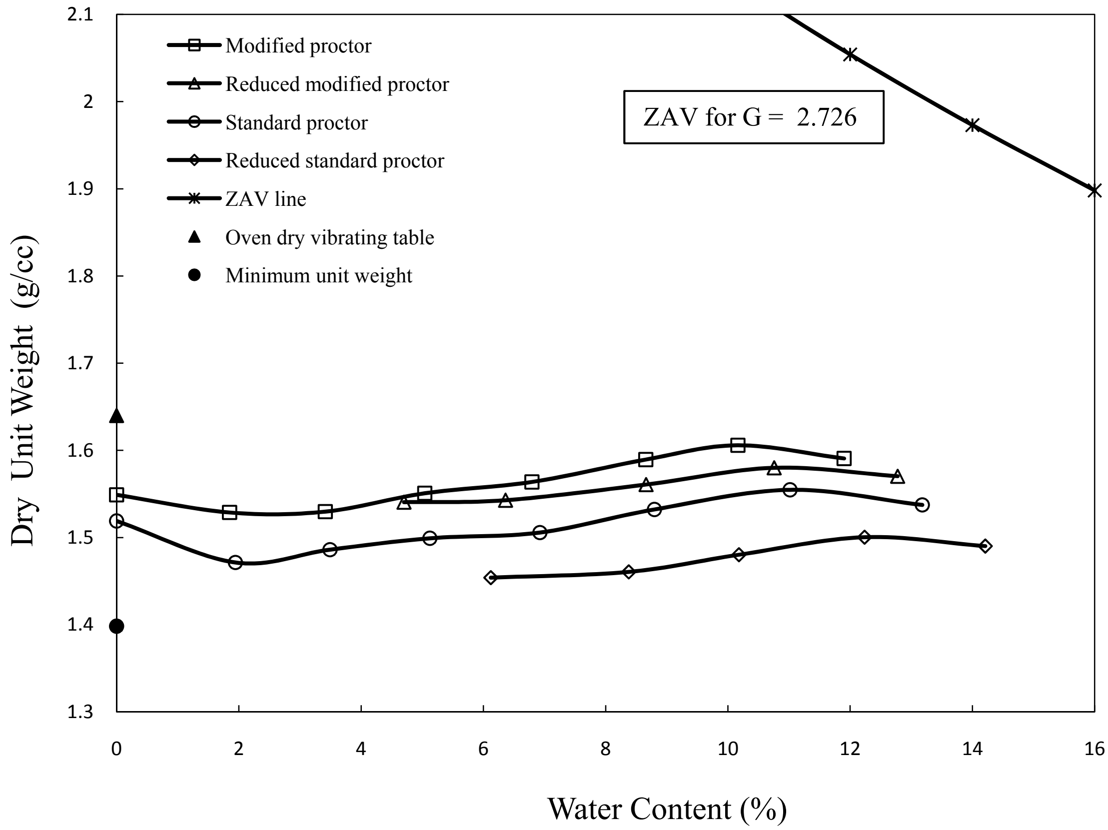

Figure A-2: Compaction results of Sample - 2

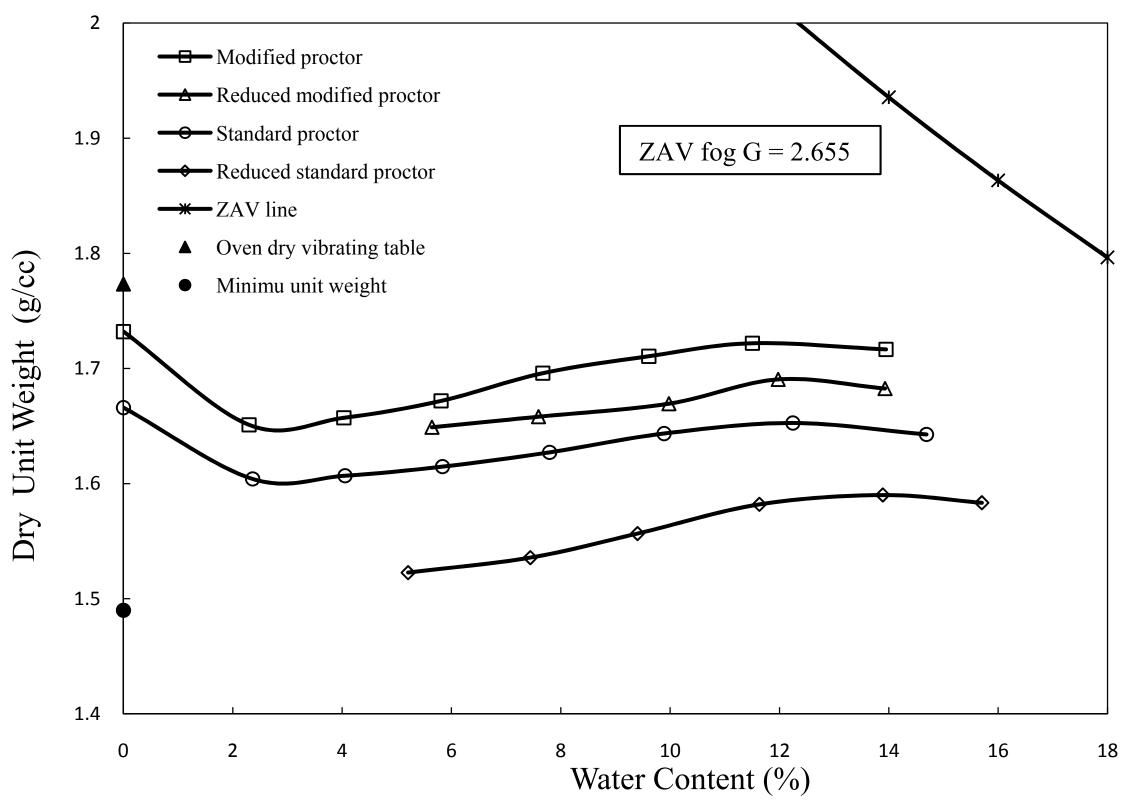

Figure A-3: Compaction results of Sample - 3

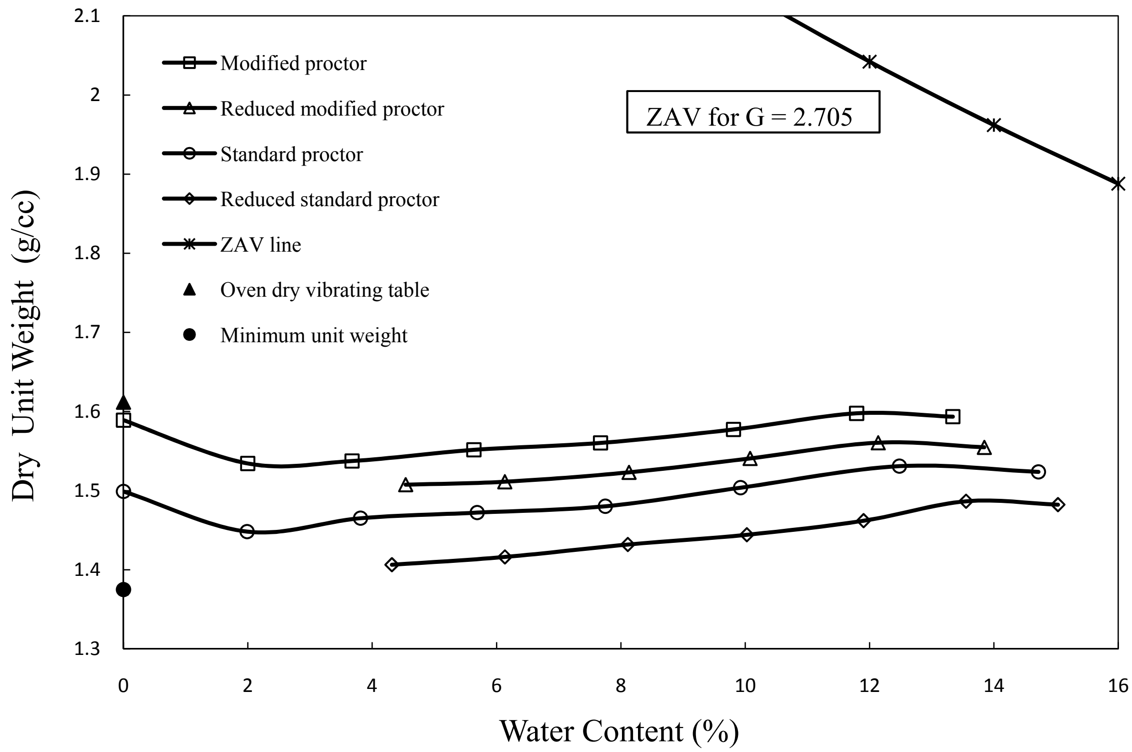

Figure A-4: Compaction results of Sample – 4

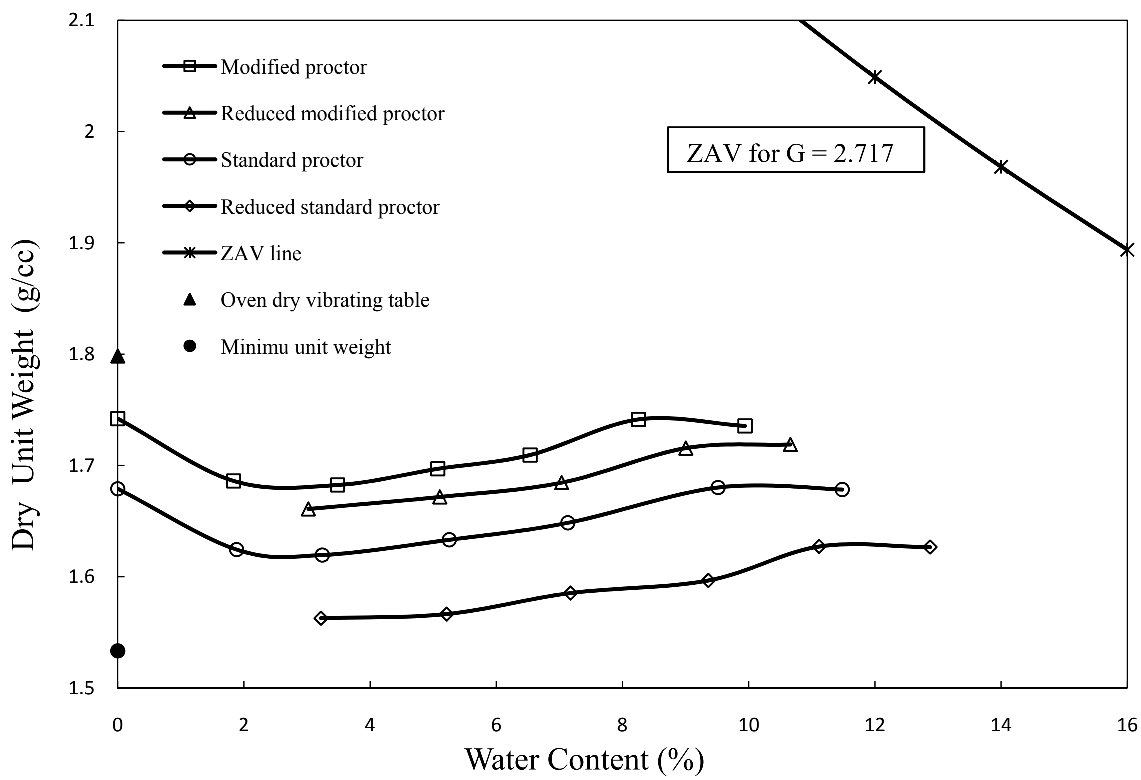

Figure A-5: Compaction results of Sample – 5

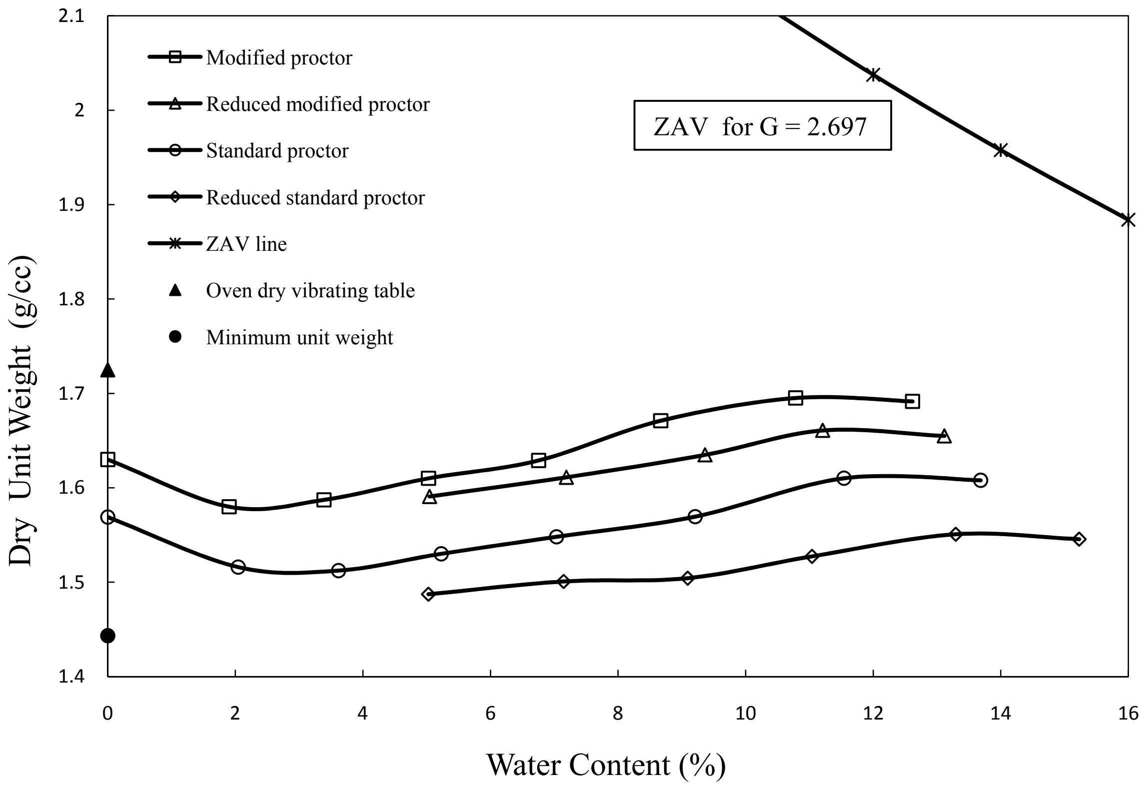

Figure A-6: Compaction results of Sample – 6

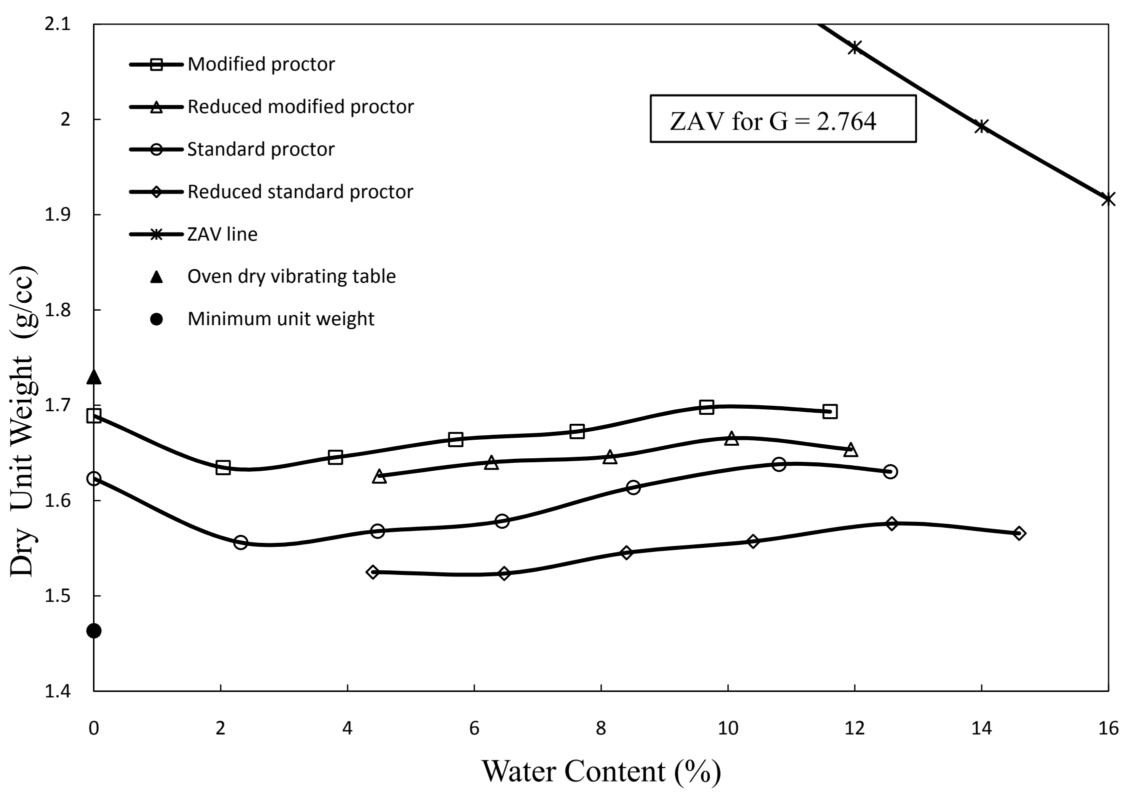

Figure A-7: Compaction results of Sample – 7

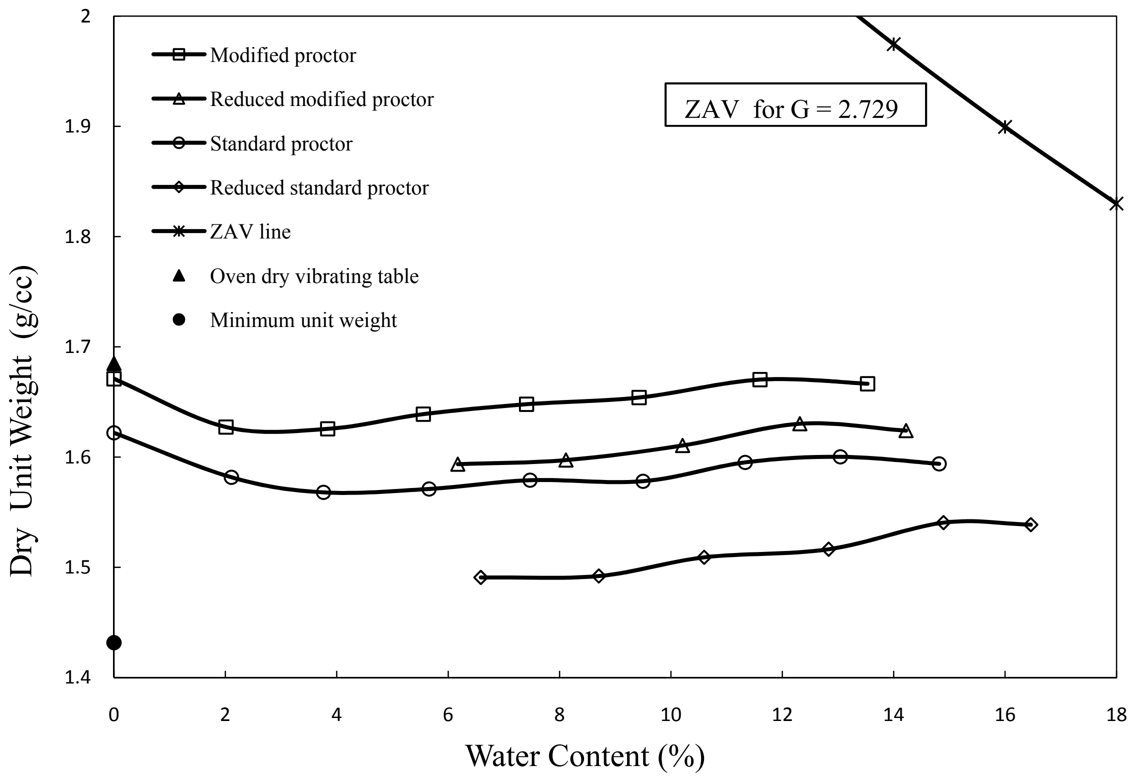

Figure A-8: Compaction results of Sample – 8

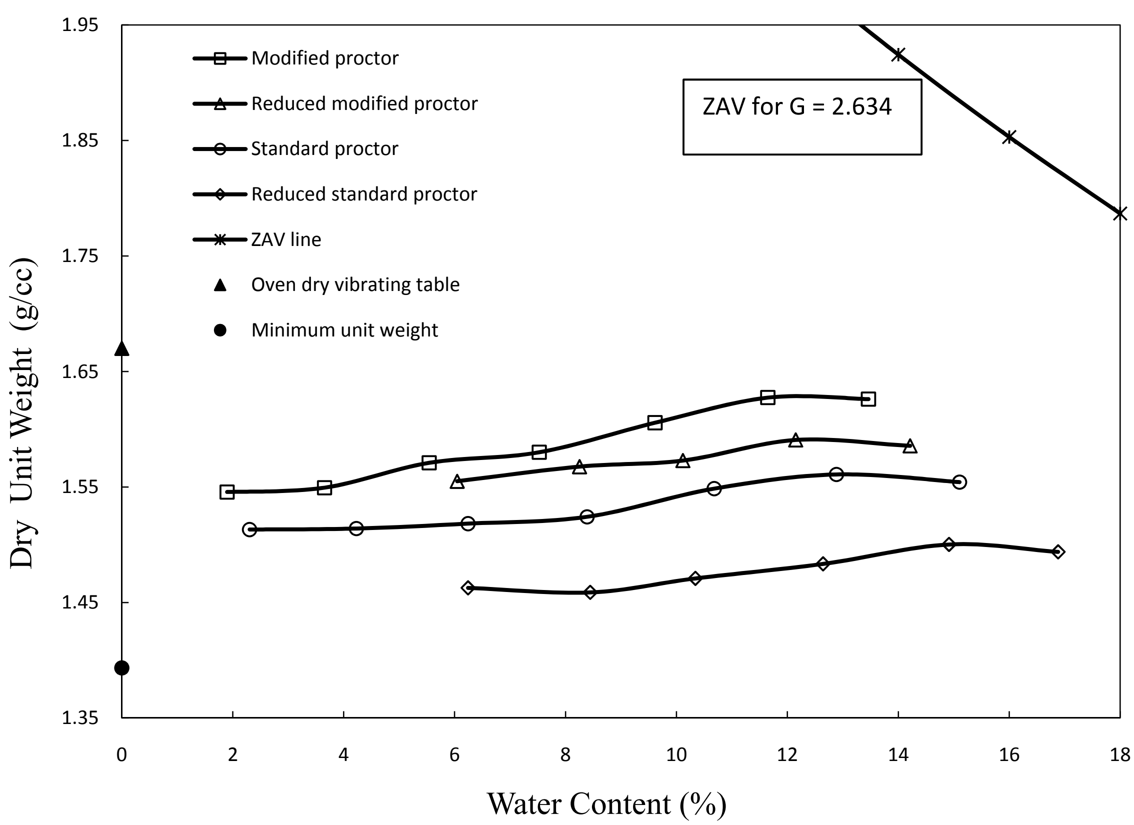

Figure A-9: Compaction results of Sample - 9

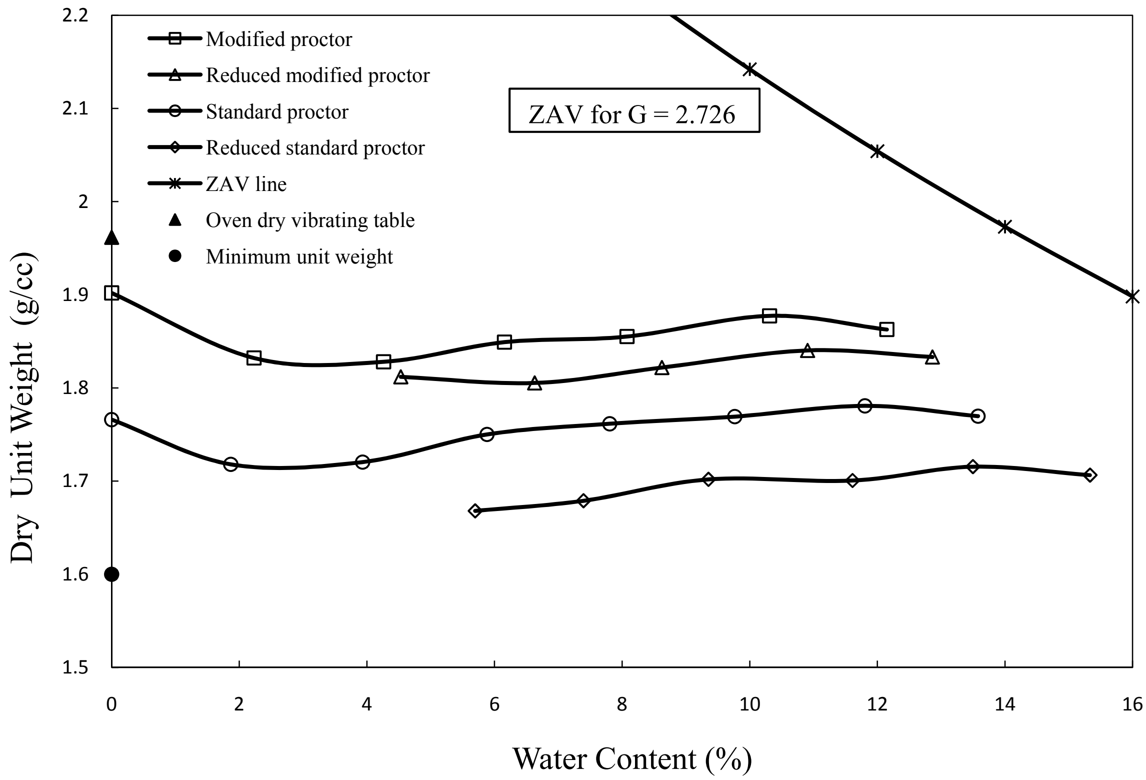

Figure A-10: Compaction results of Sample -10

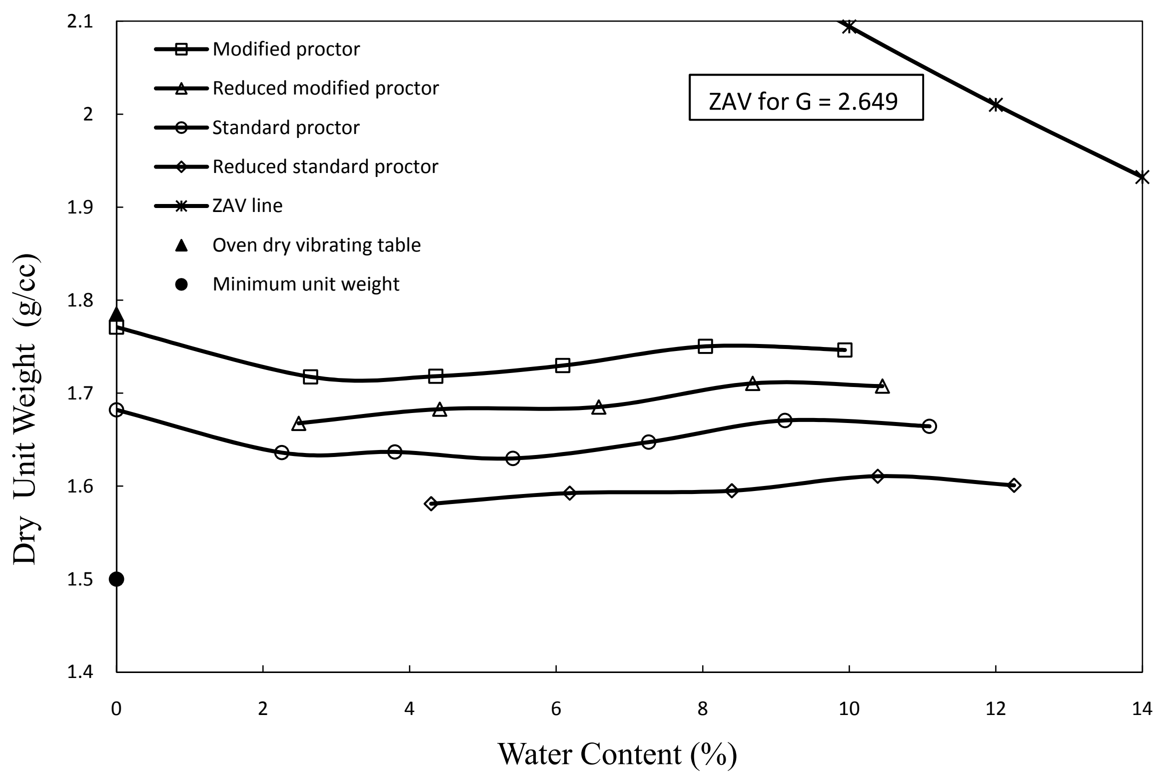

Figure A-11: Compaction results of Sample -11

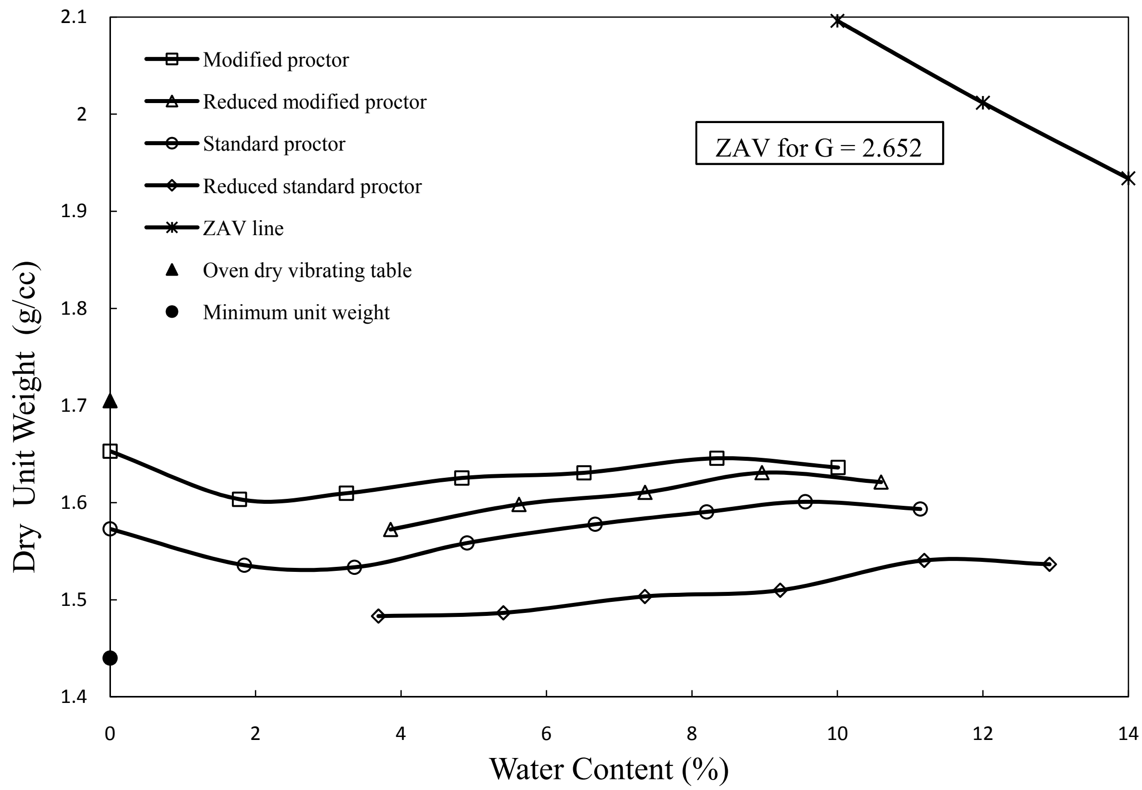

Figure A-12: Compaction results of Sample -12

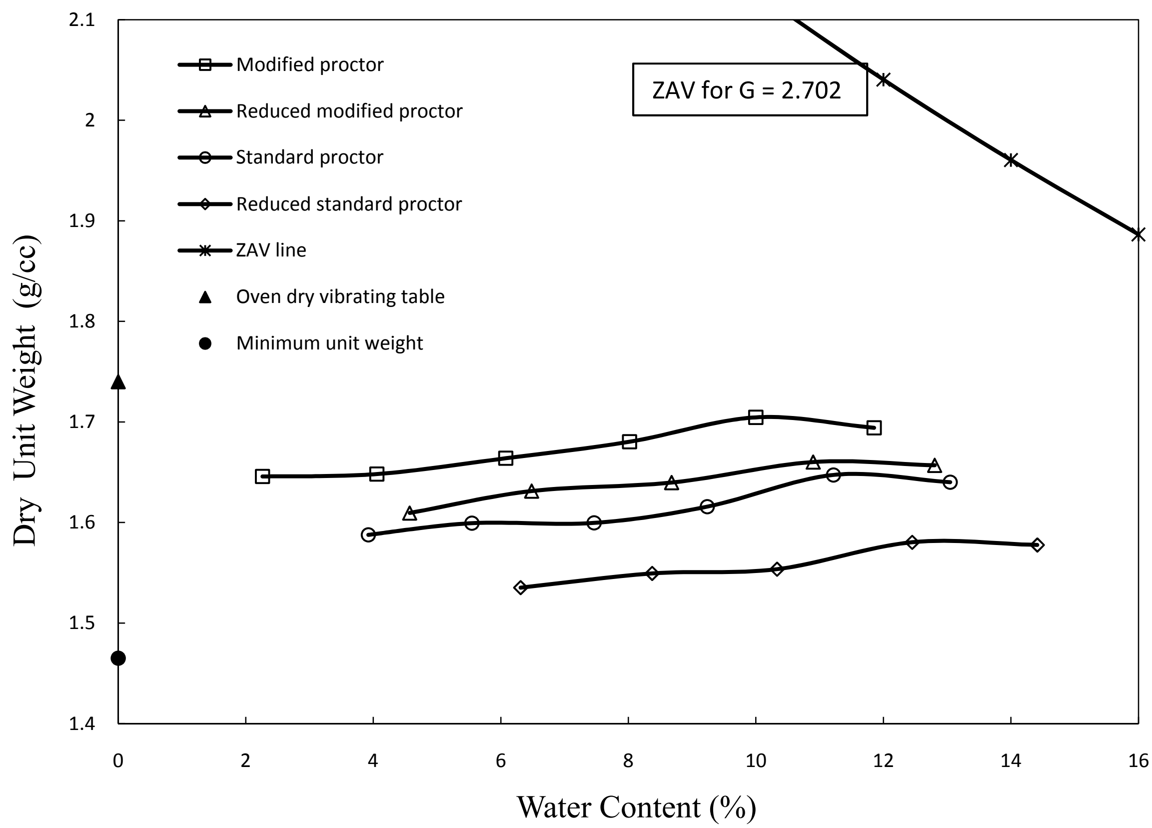

Figure A-13: Compaction results of Sample -13

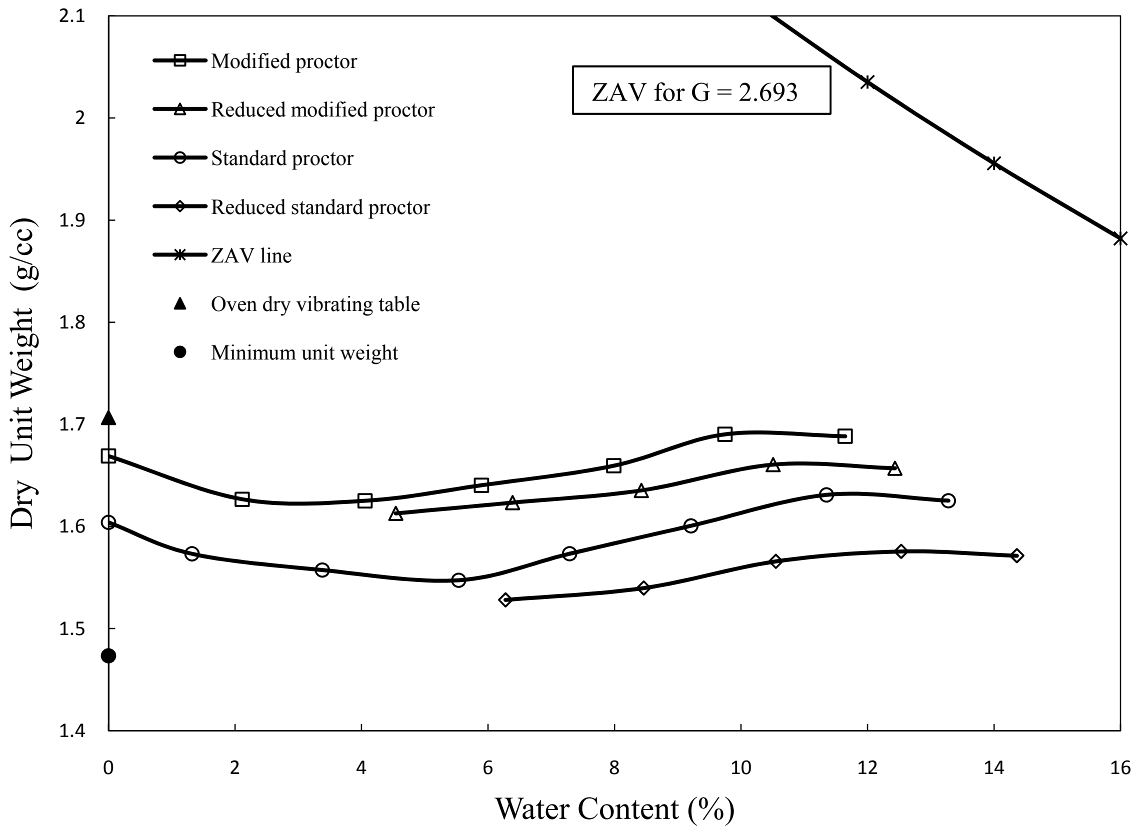

Figure A-14: Compaction results of Sample -14

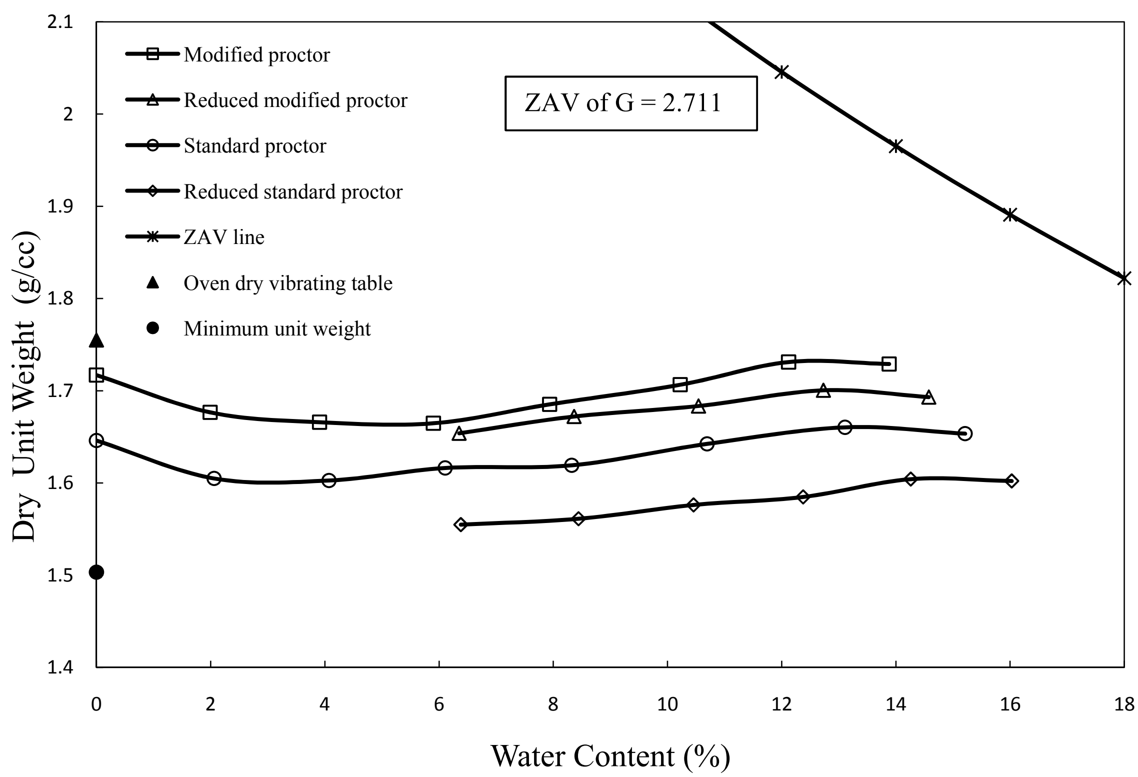

Figure A-15: Compaction results of Sample -15

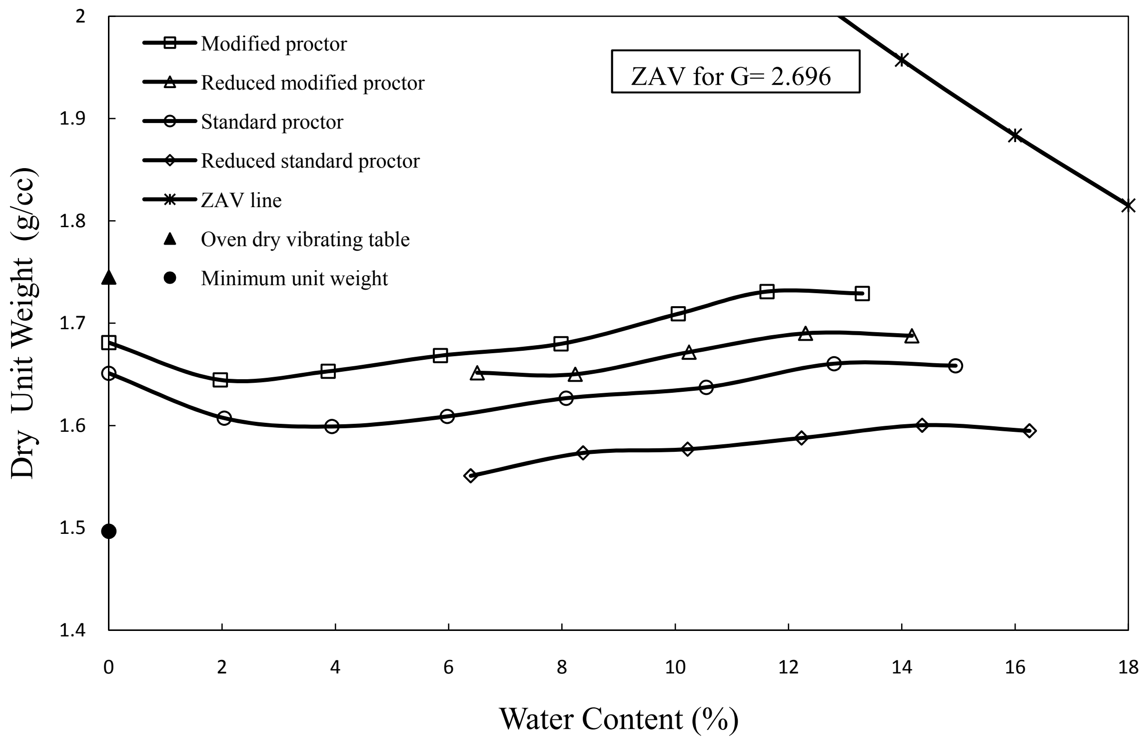

Figure A-16: Compaction results of Sample -16

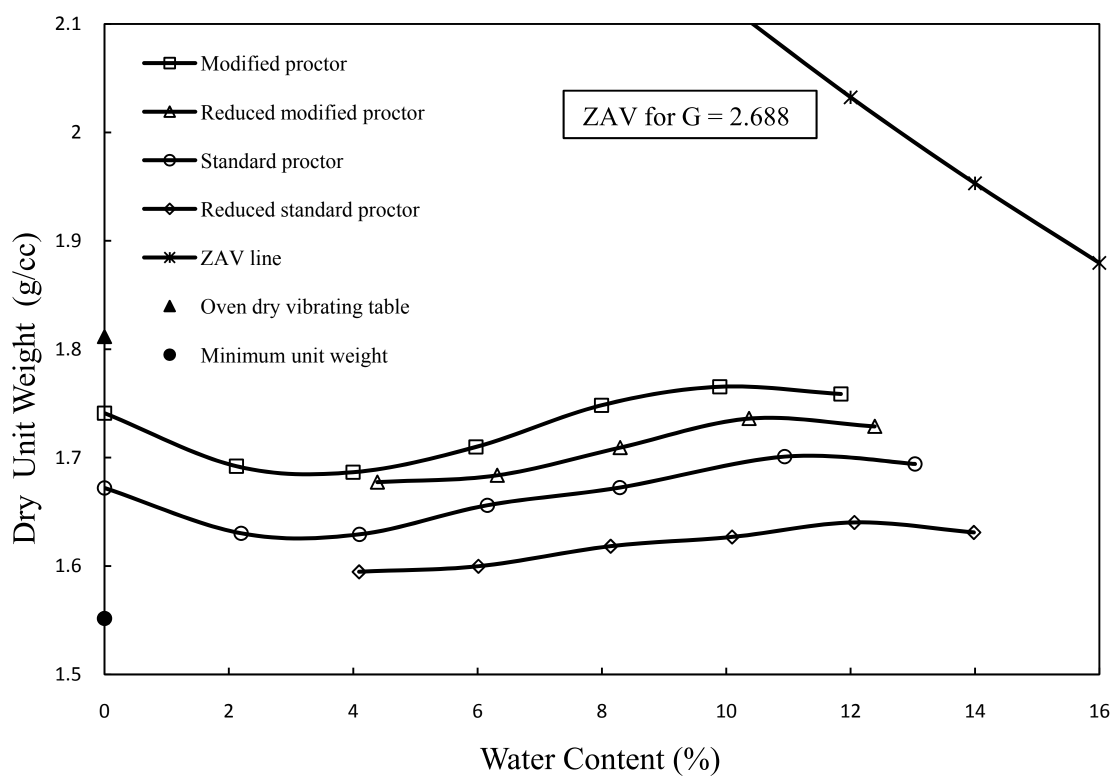

Figure A-17: Compaction results of Sample -17

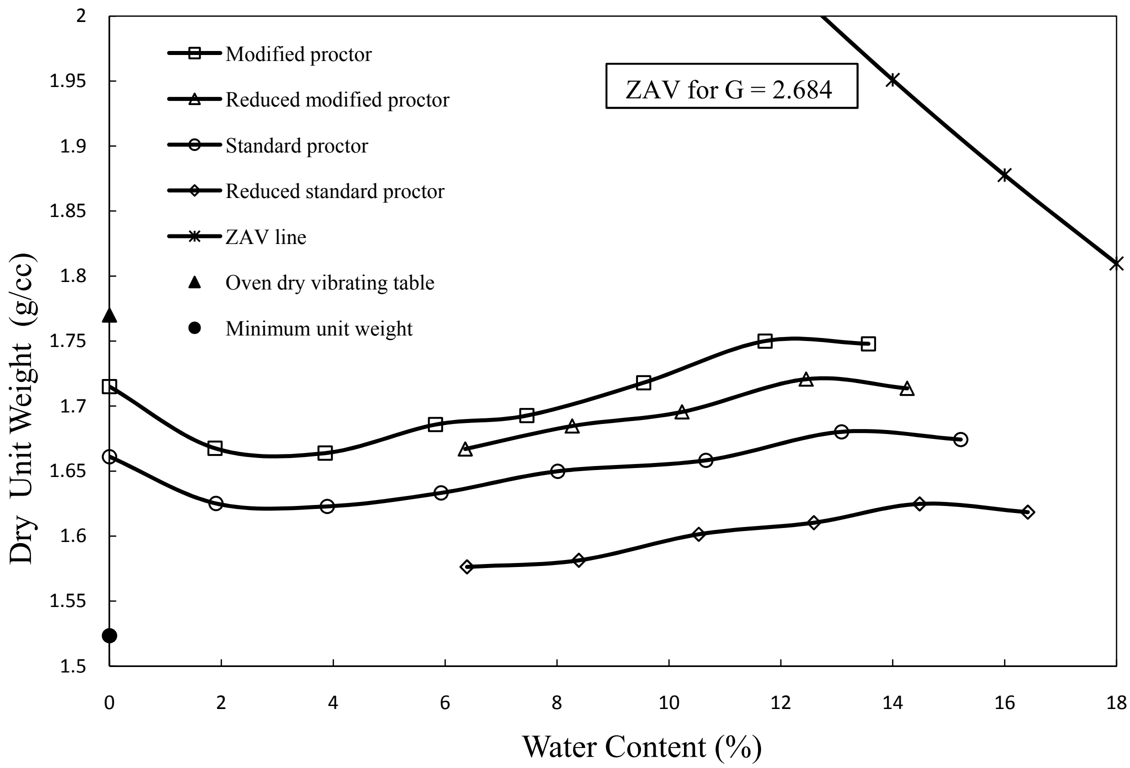

Figure A-18: Compaction results of Sample -18

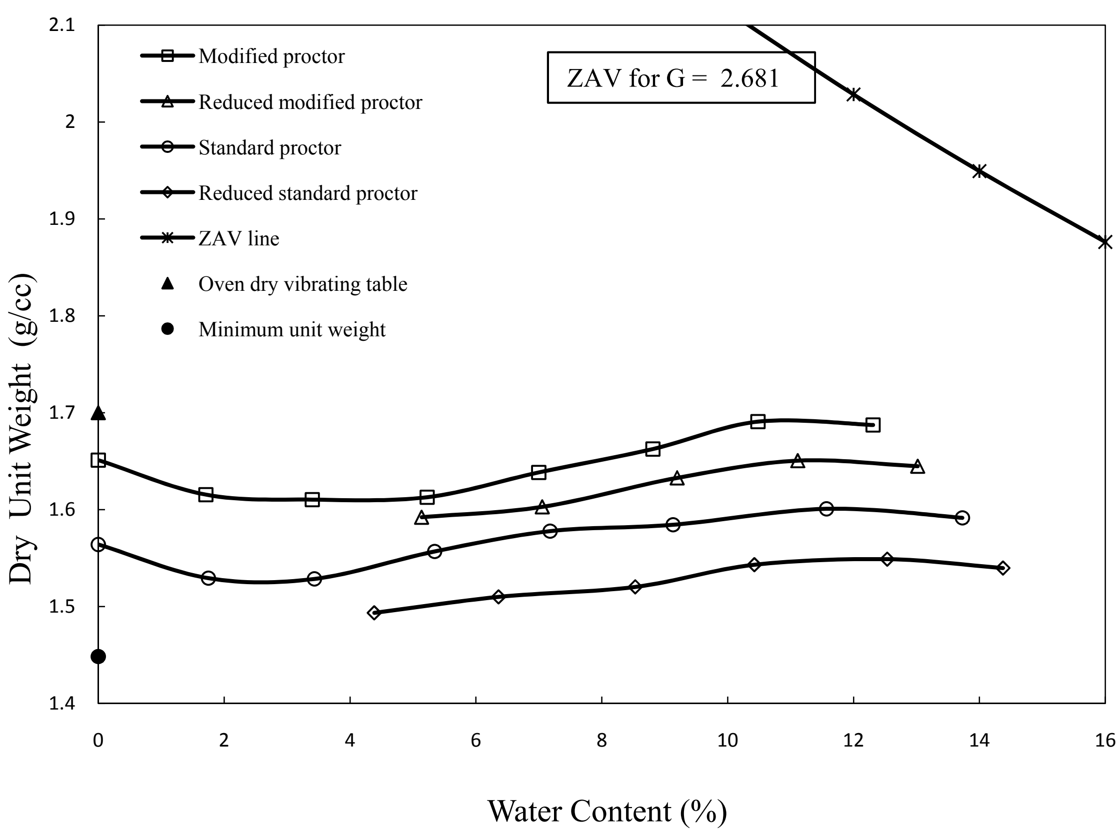

Figure A-19: Compaction results of Sample -19

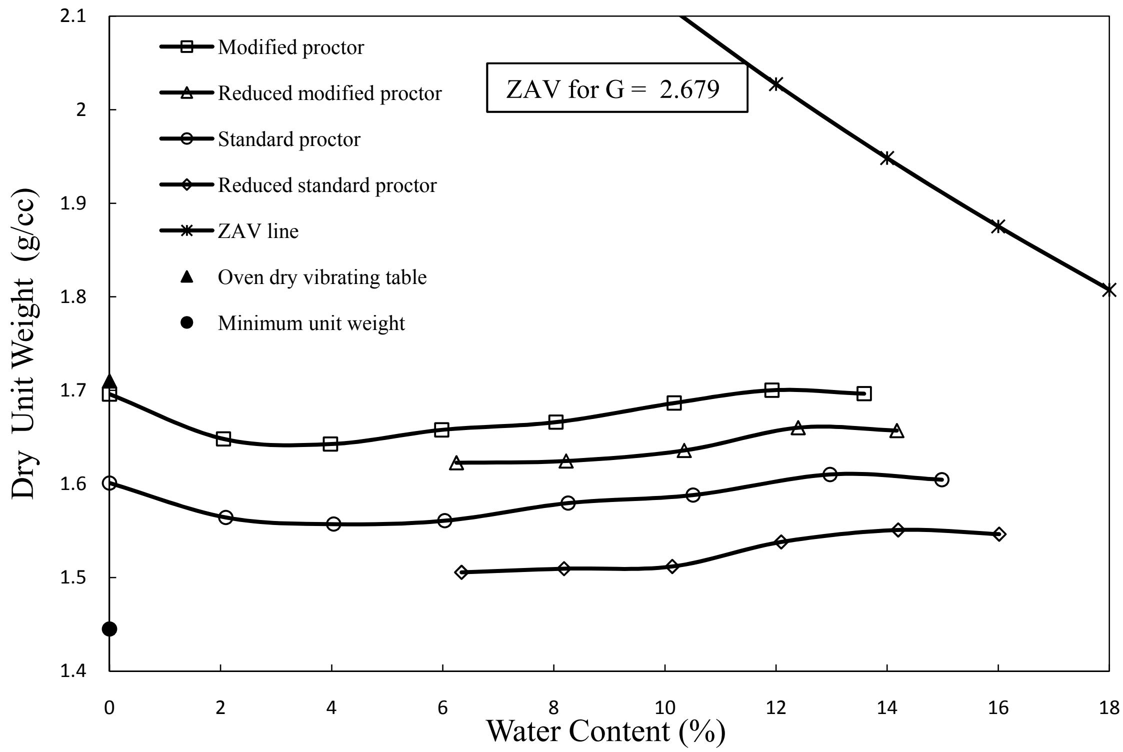

Figure A-20: Compaction results of Sample -20

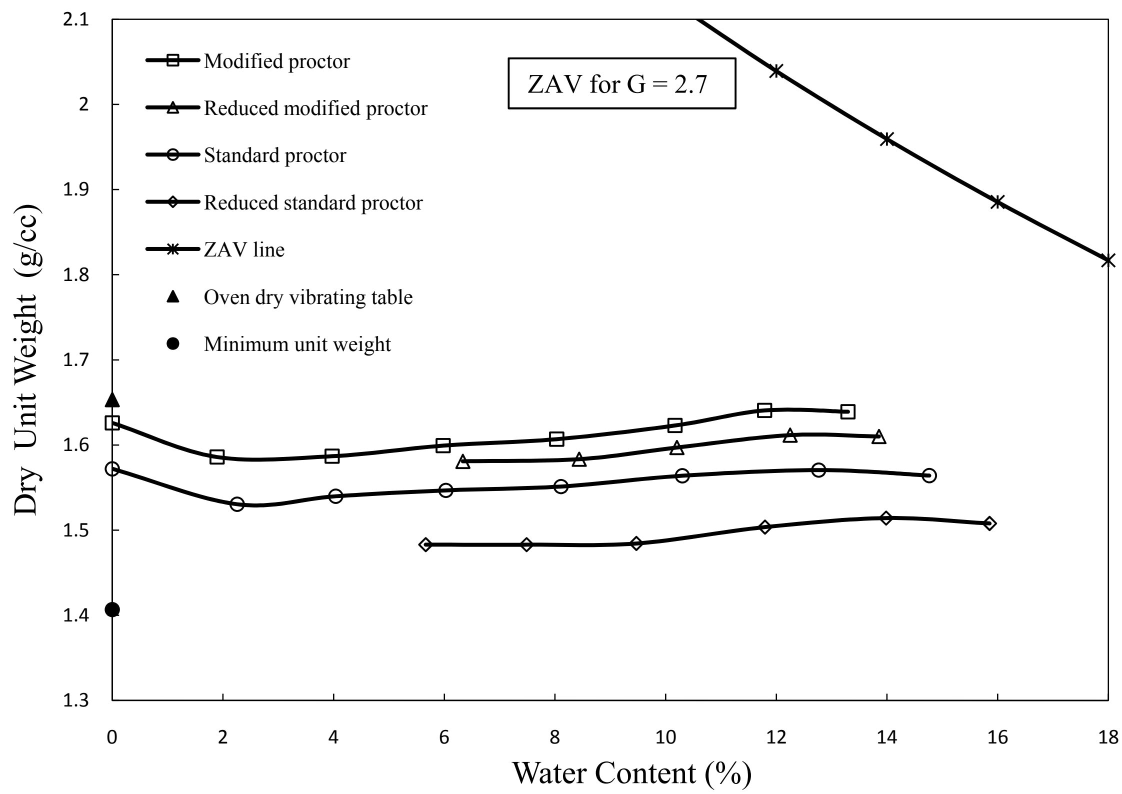

Figure A-21: Compaction results of Sample -21

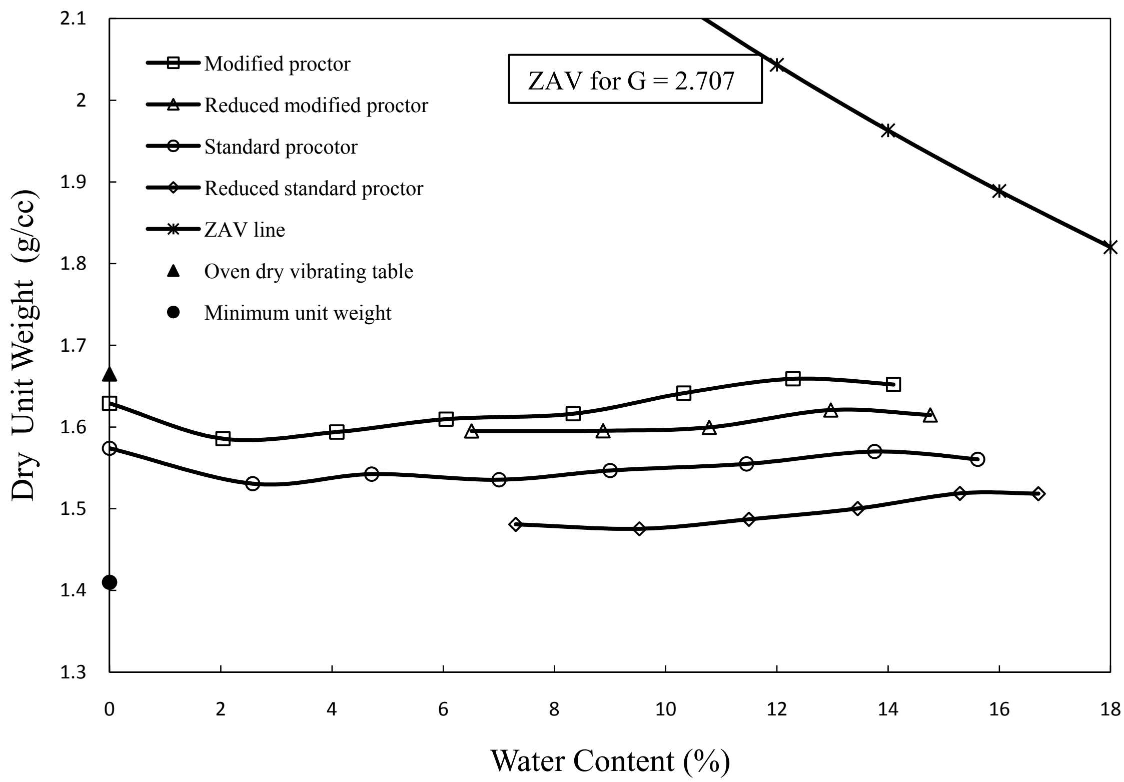

Figure A-22: Compaction results of Sample -22

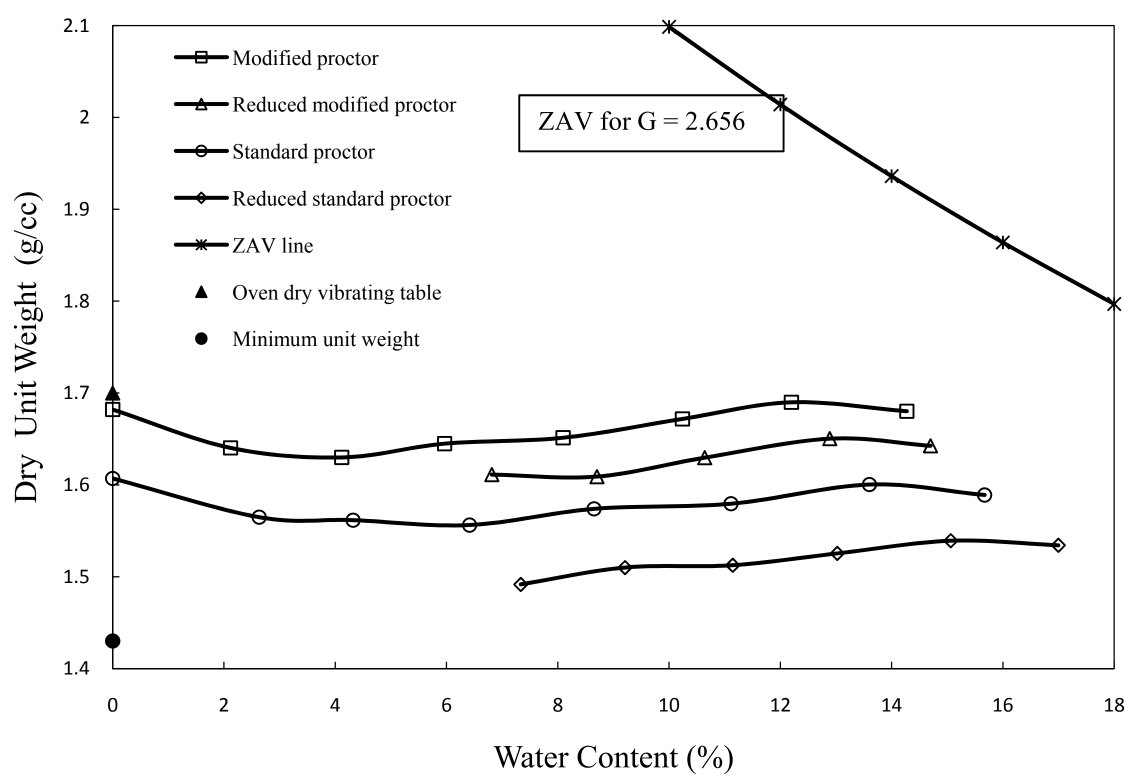

Figure A-23: Compaction results of Sample -23

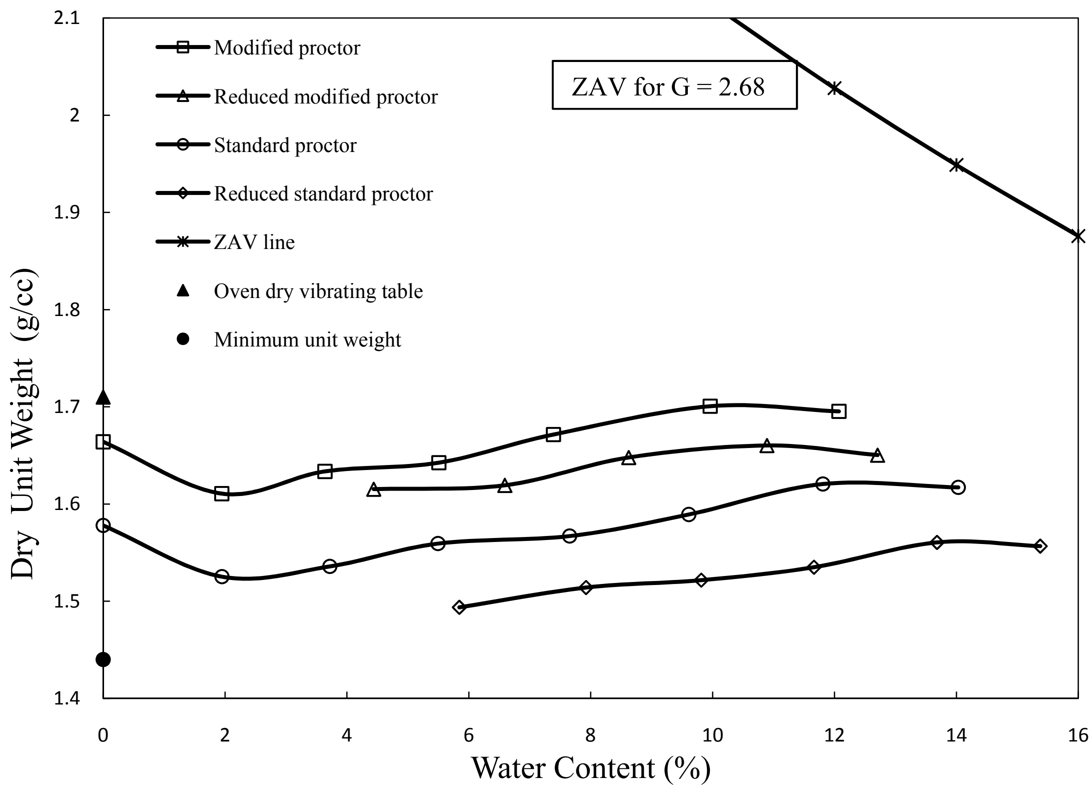

Figure A-24: Compaction results of Sample -24

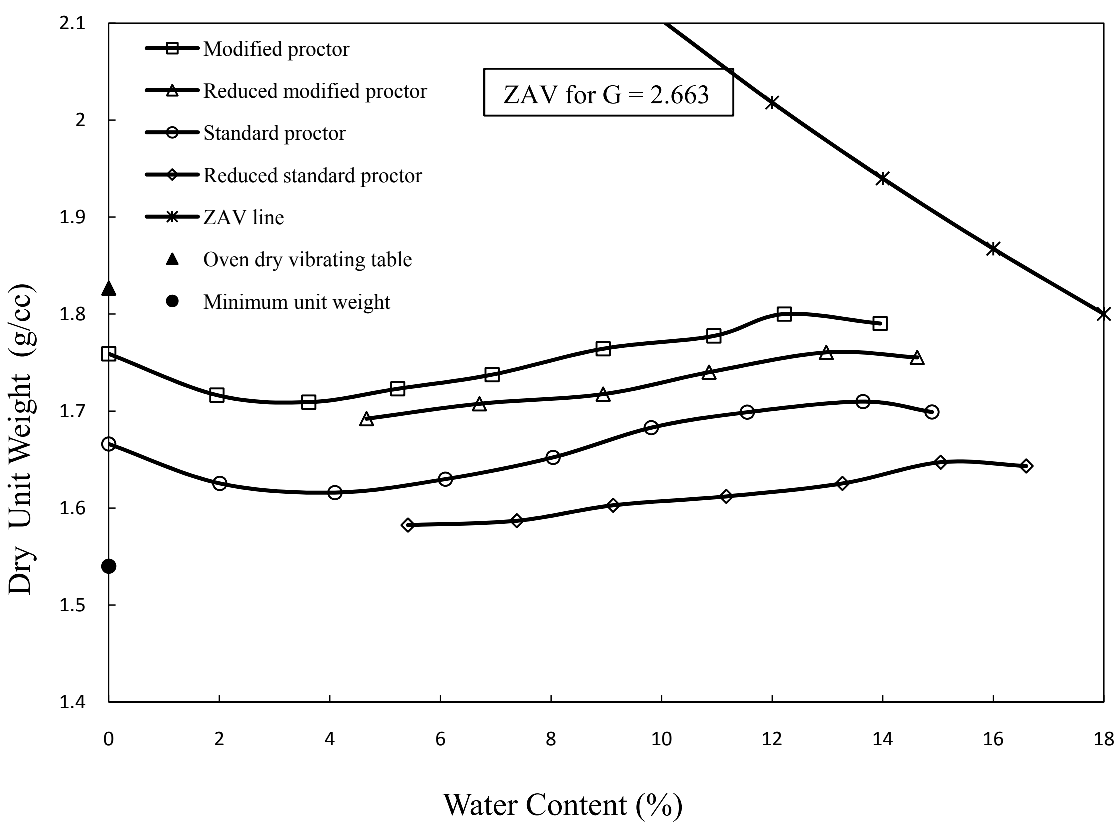

Figure A-25: Compaction results of Sample -25

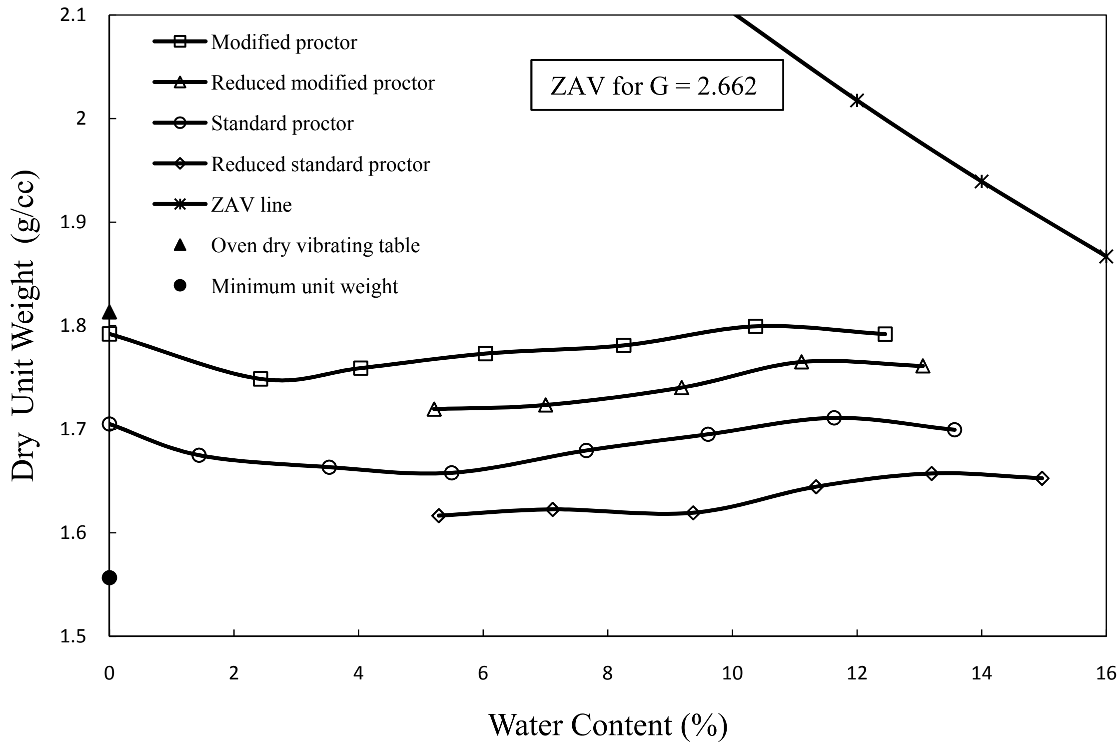

Figure A-26: Compaction results of Sample -26

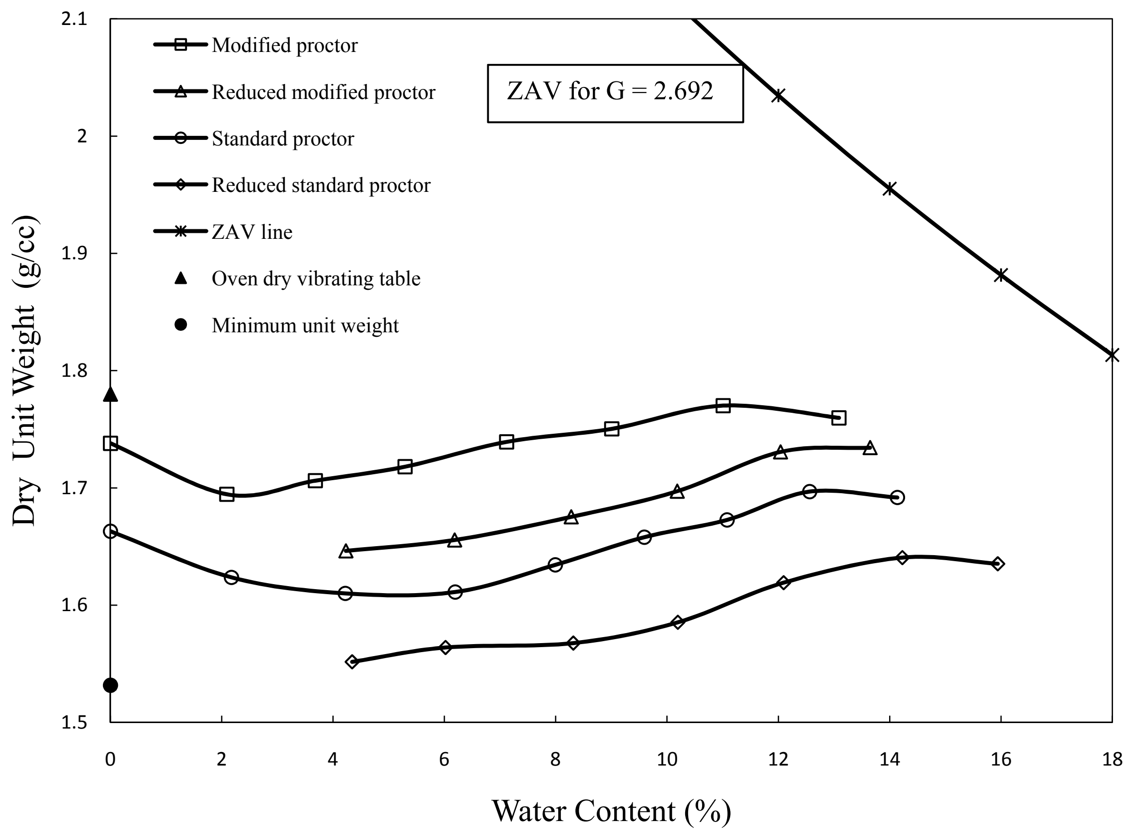

Figure A-27: Compaction results of Sample -27

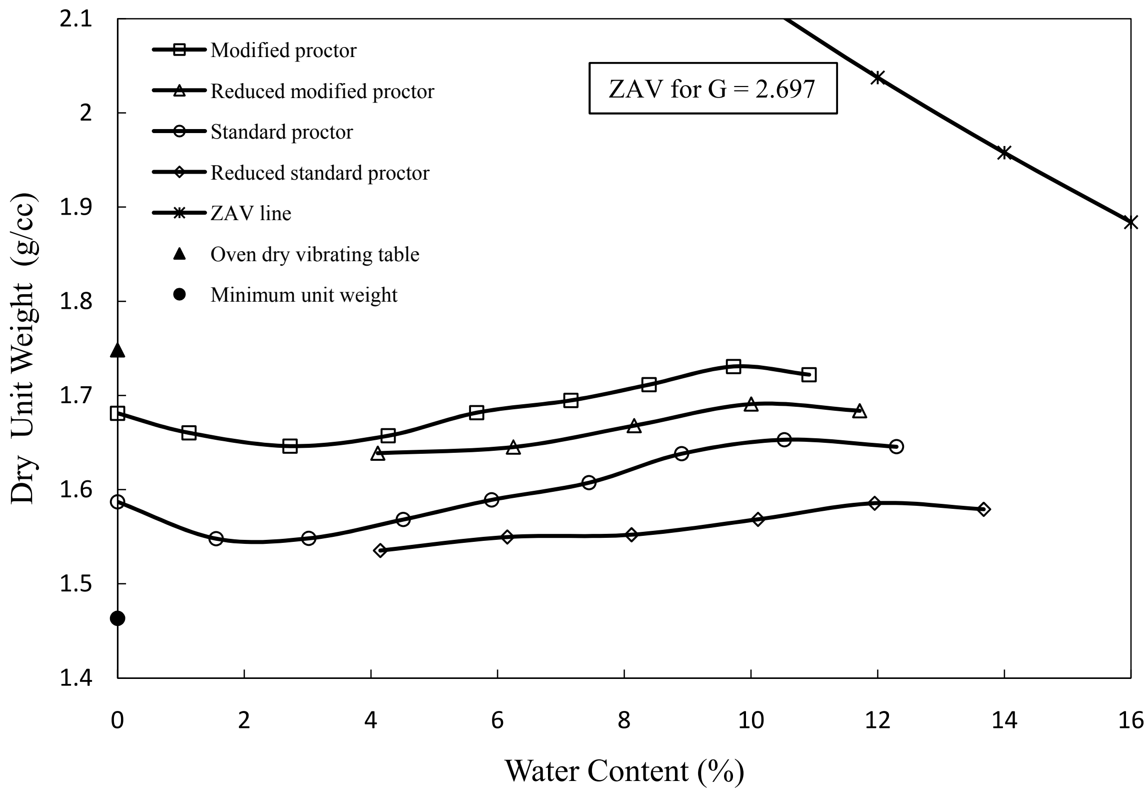

Figure A-28: Compaction results of Sample -28

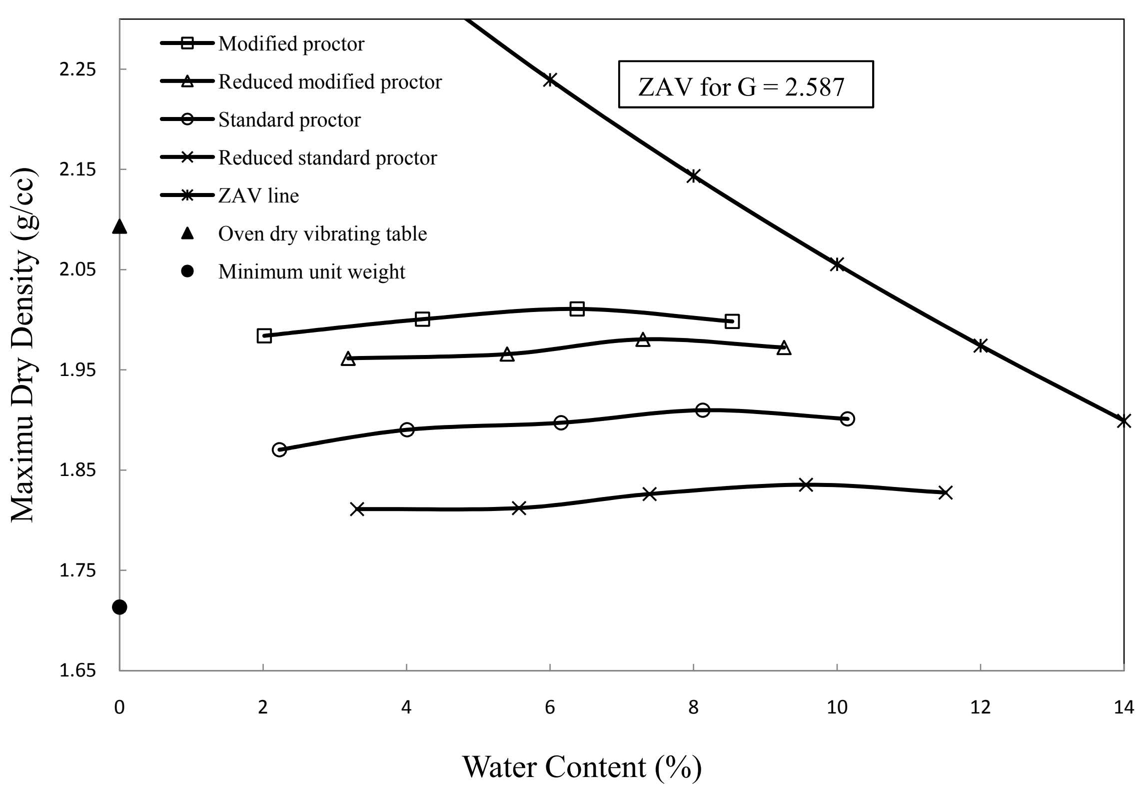

Figure A-29: Compaction results of Sample -29

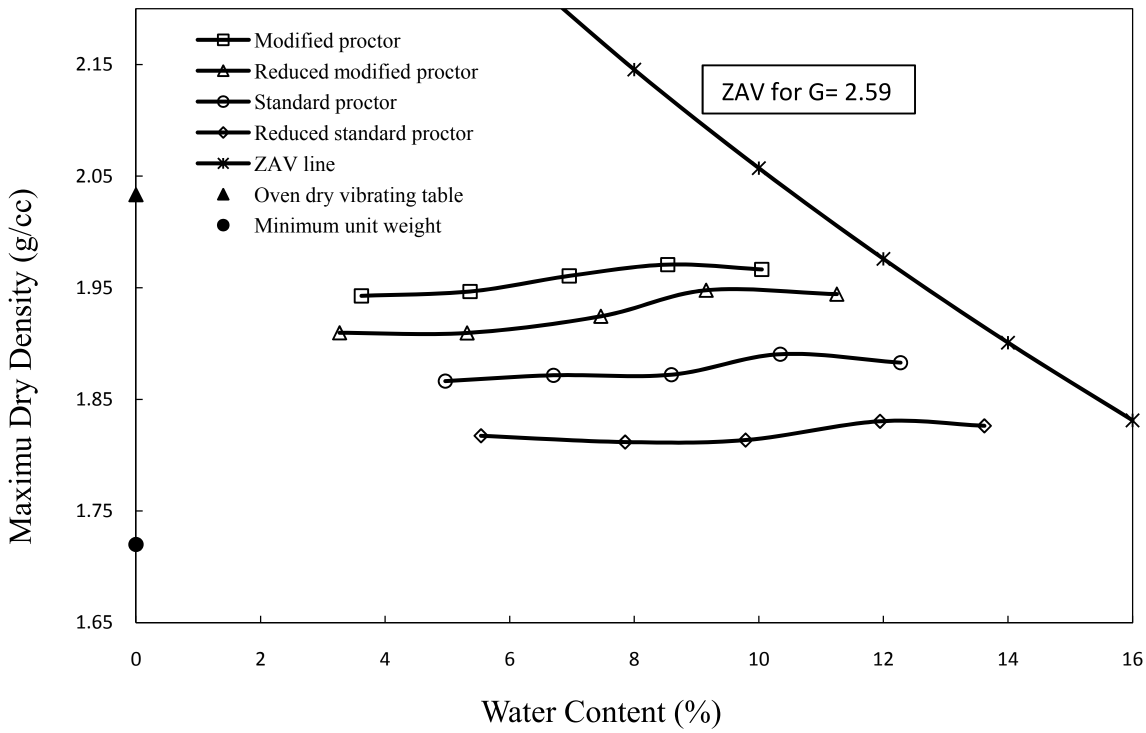

Figure A-30: Compaction results of Sample -30

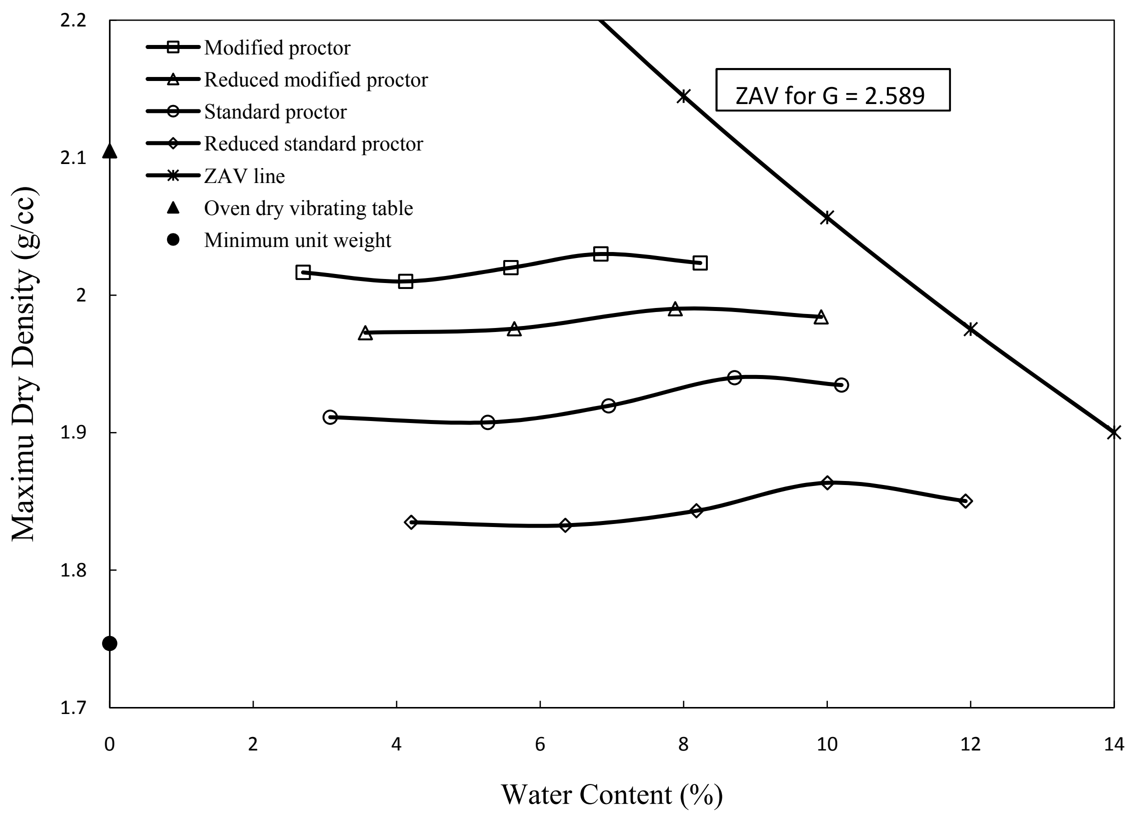

Figure A-31: Compaction results of Sample -31

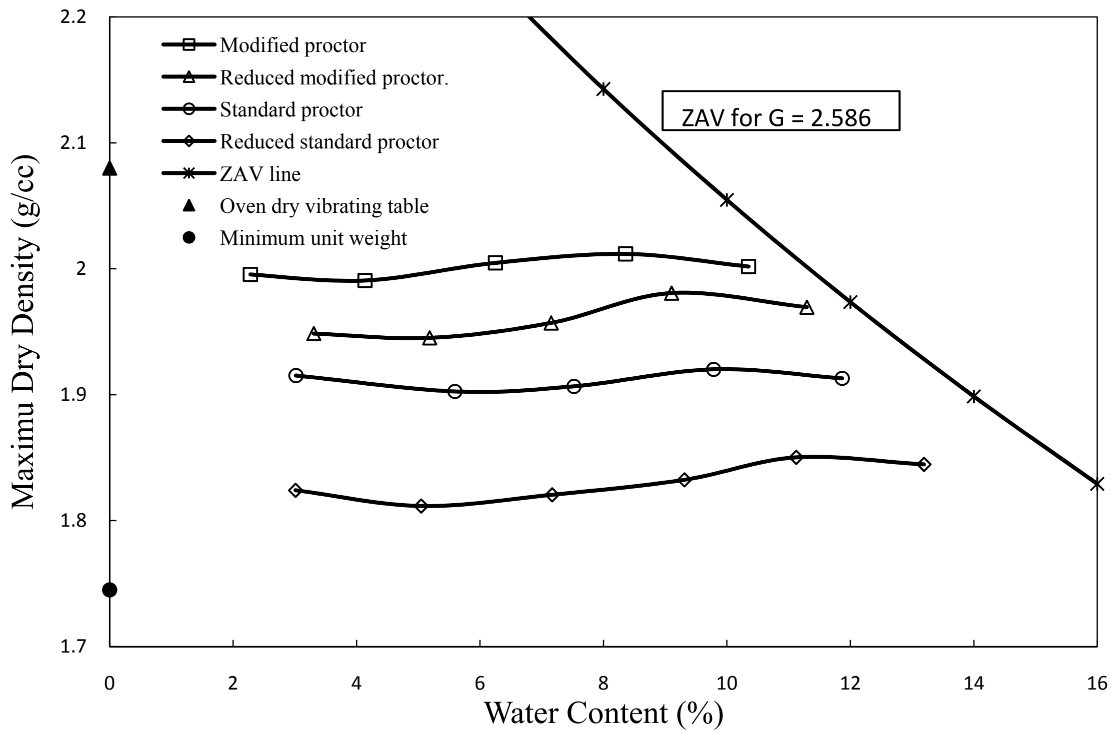

Figure A-32: Compaction results of Sample -32

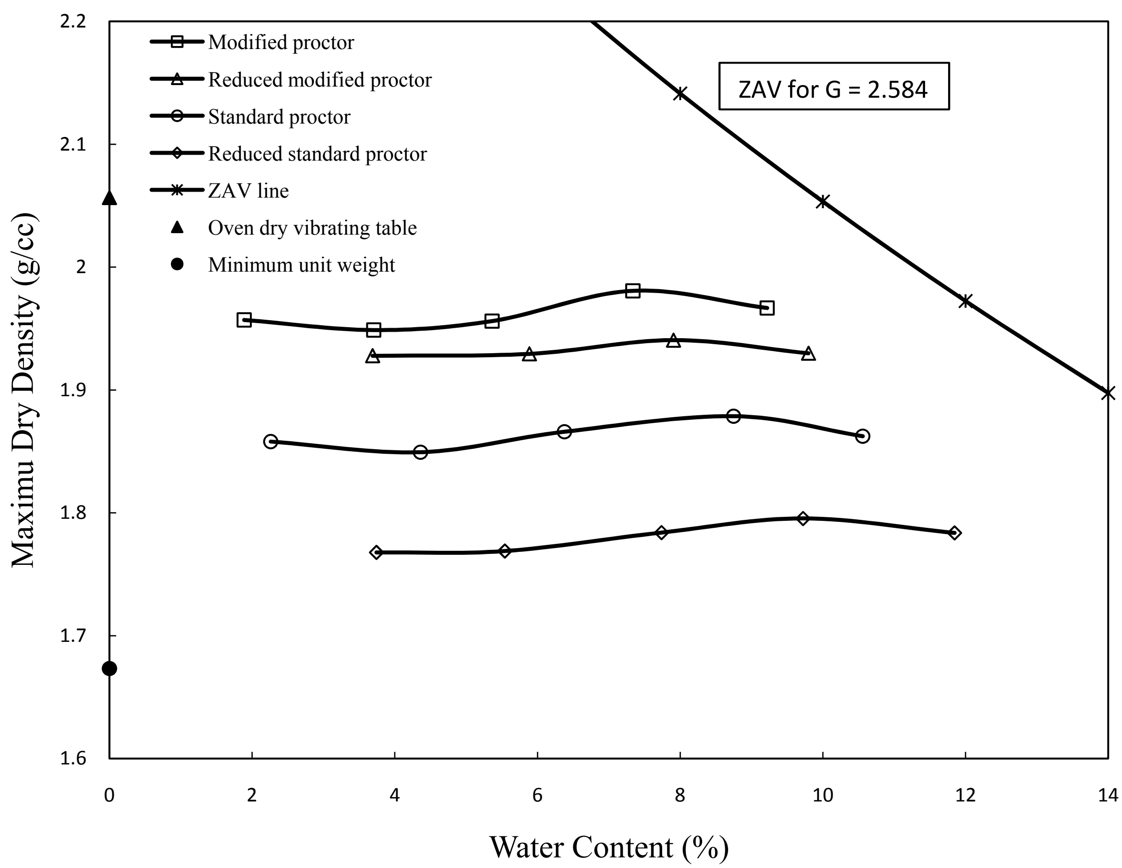

Figure A-33: Compaction results of Sample -33

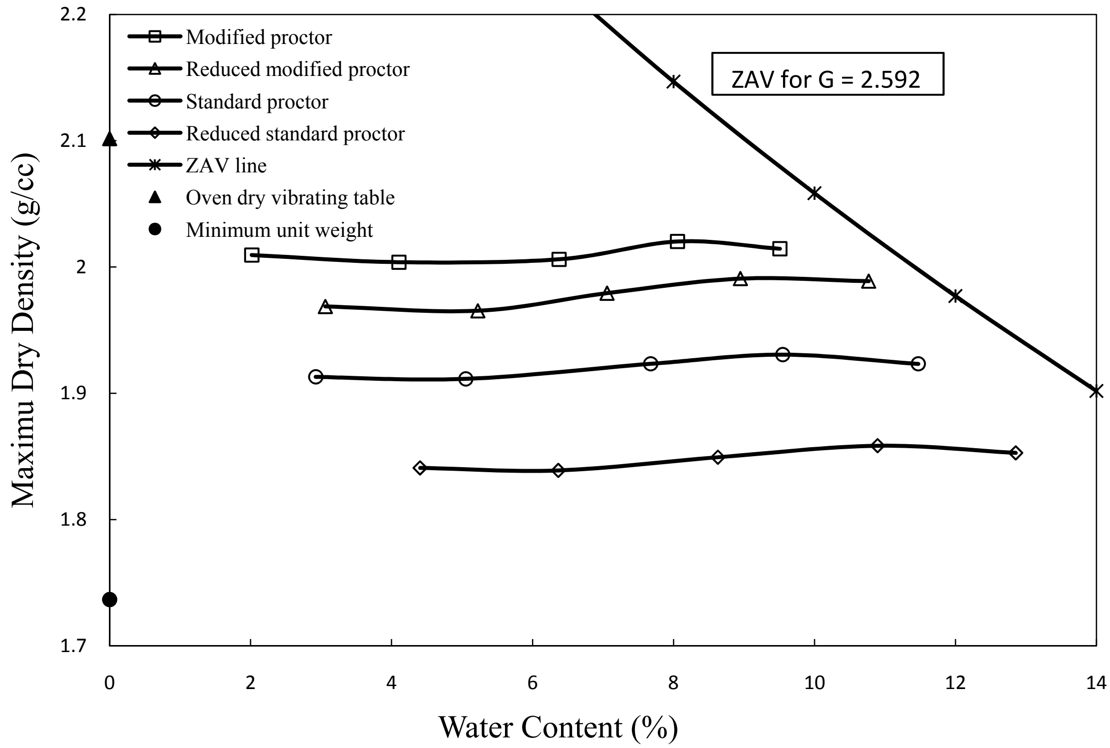

Figure A-34: Compaction results of Sample -34

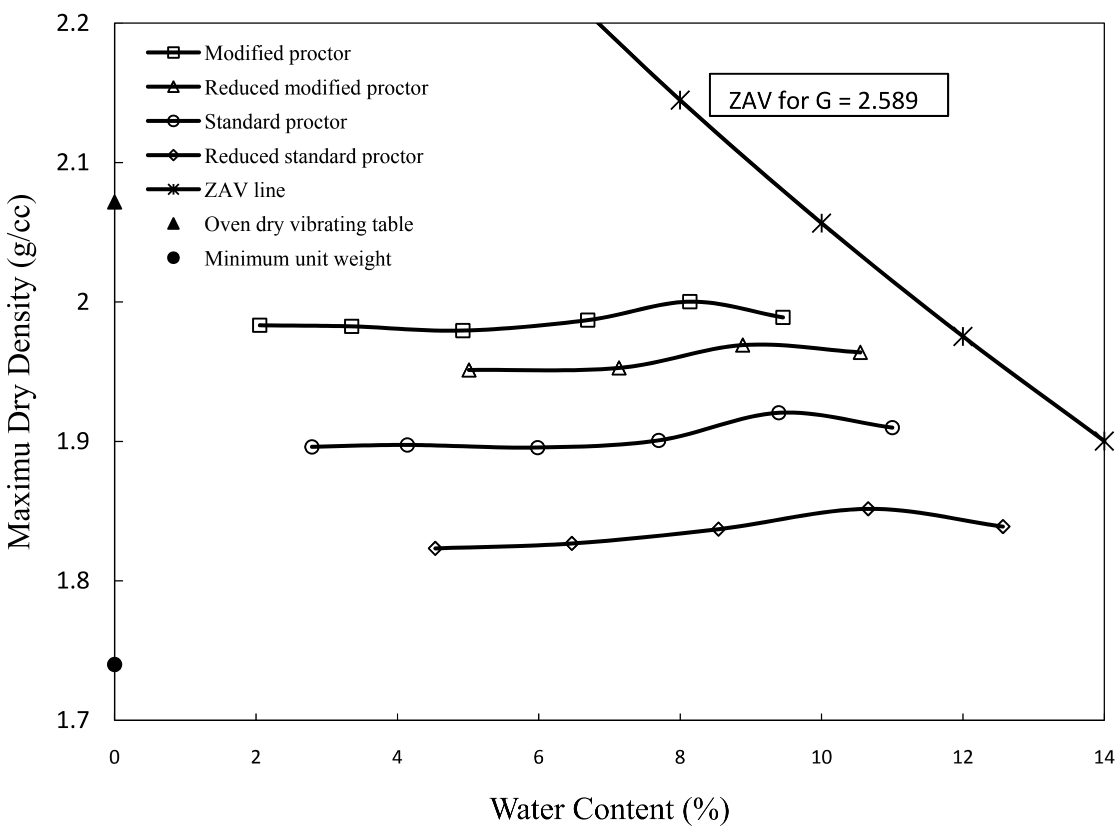

Figure A-35: Compaction results of Sample -35

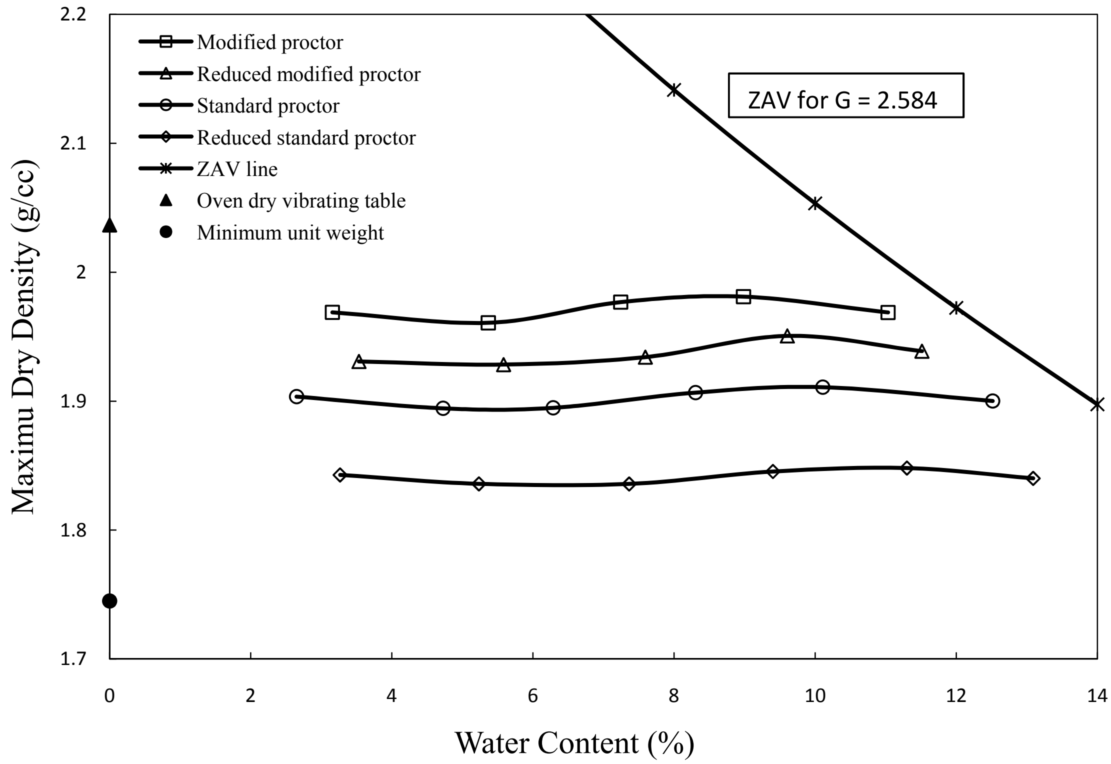

Figure A-36: Compaction results of Sample -36

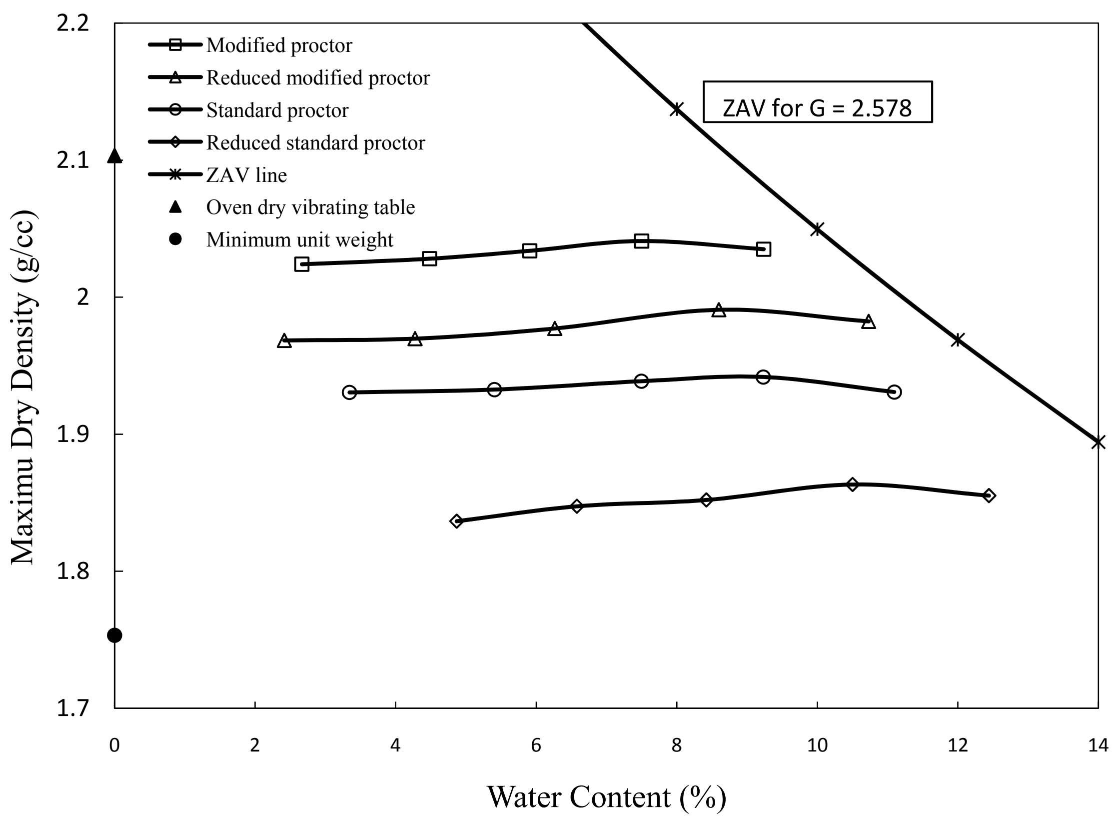

Figure A-37: Compaction results of Sample -37

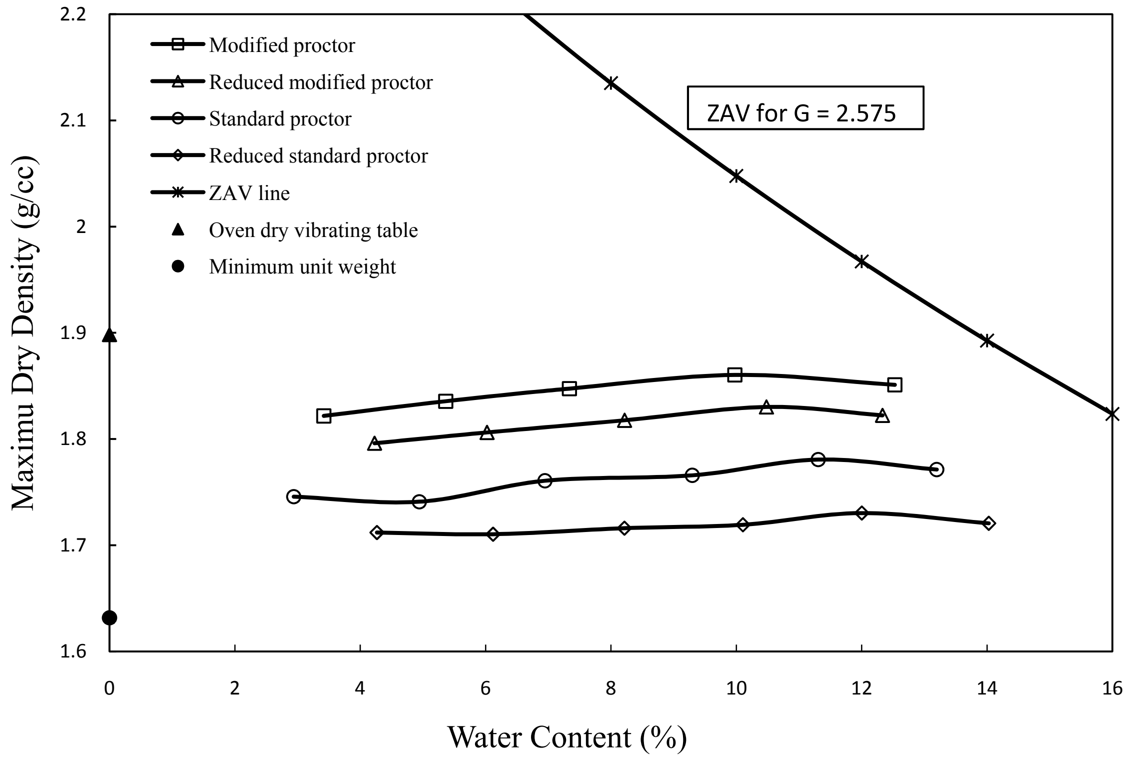

Figure A-38: Compaction results of Sample -38

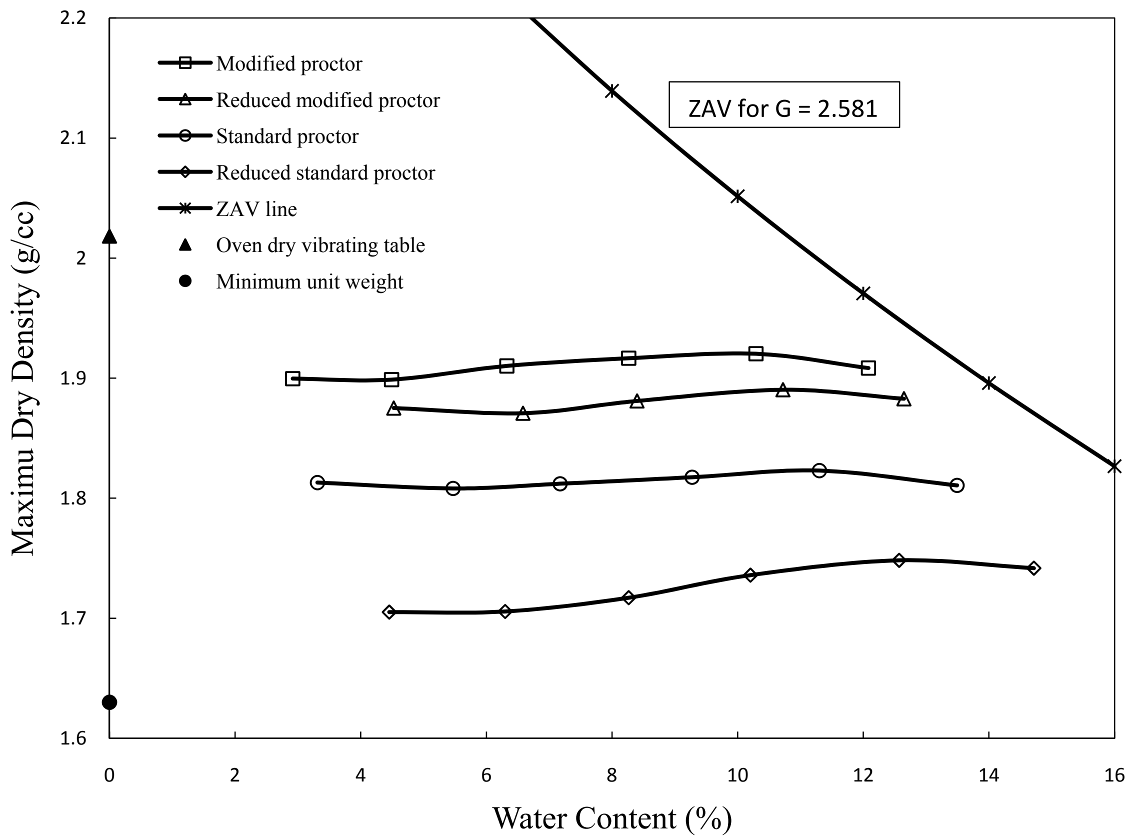

Figure A-39: Compaction results of Sample -39

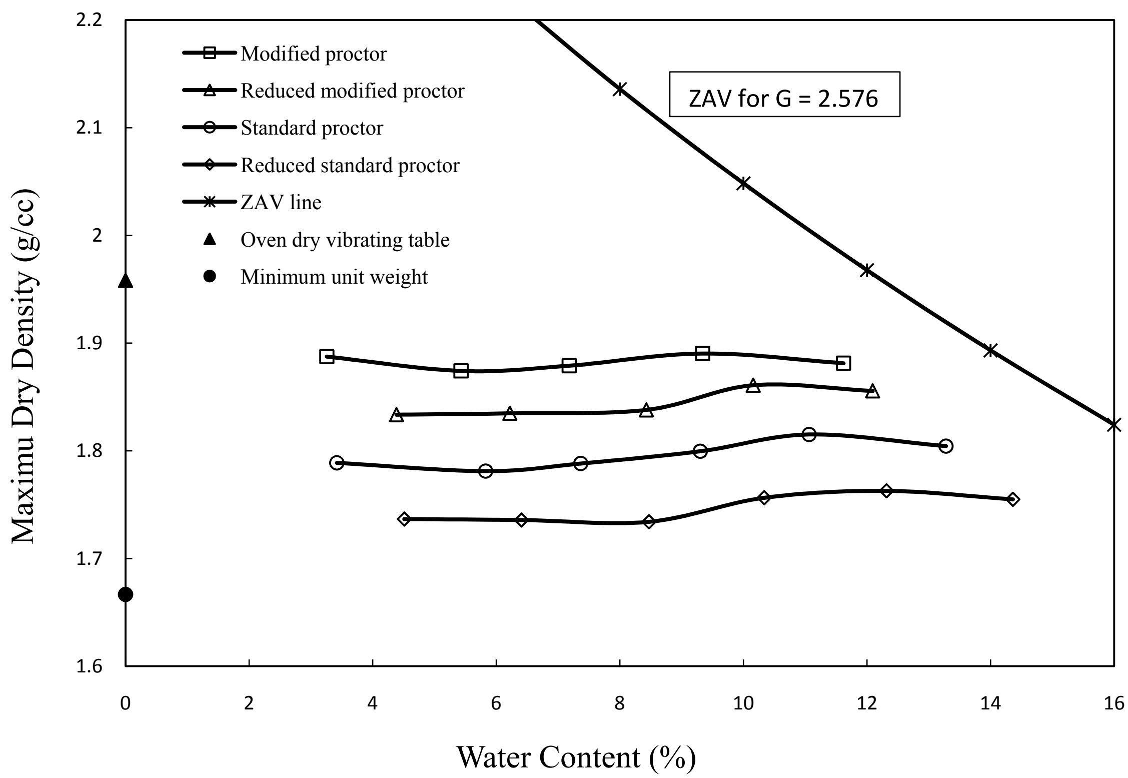

Figure A-40: Compaction results of Sample -40

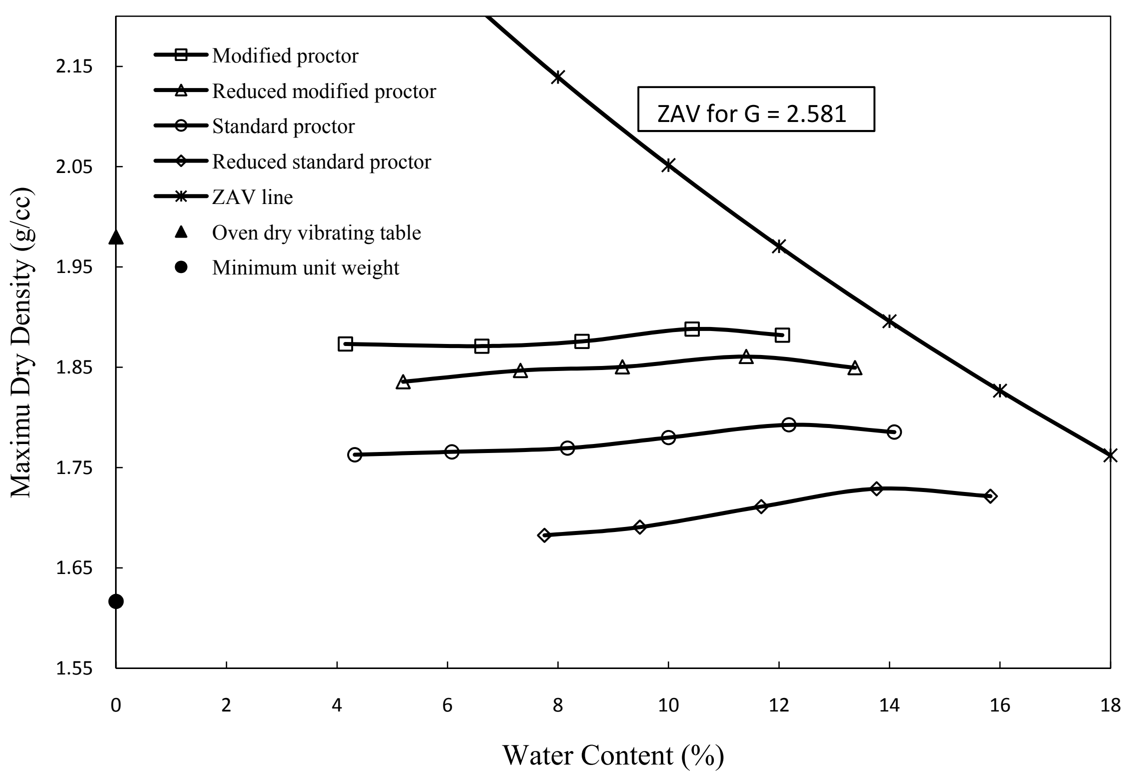

Figure A-41: Compaction results of Sample -41

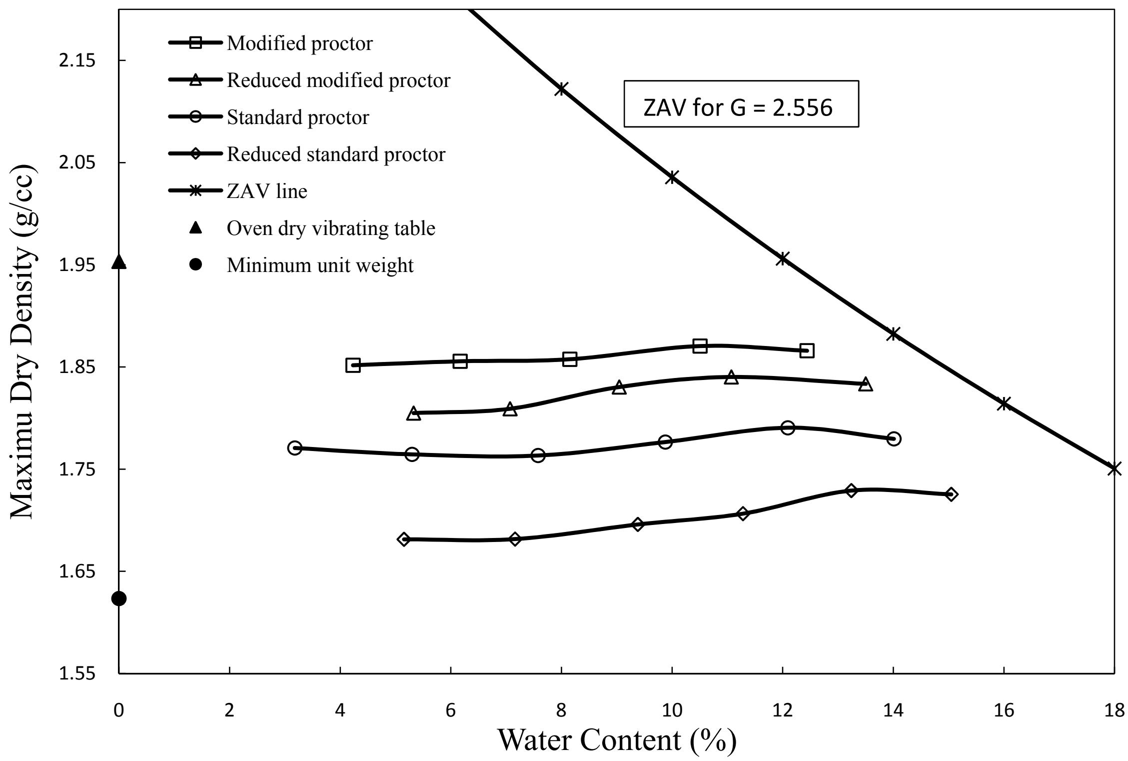

Figure A-42: Compaction results of Sample -42

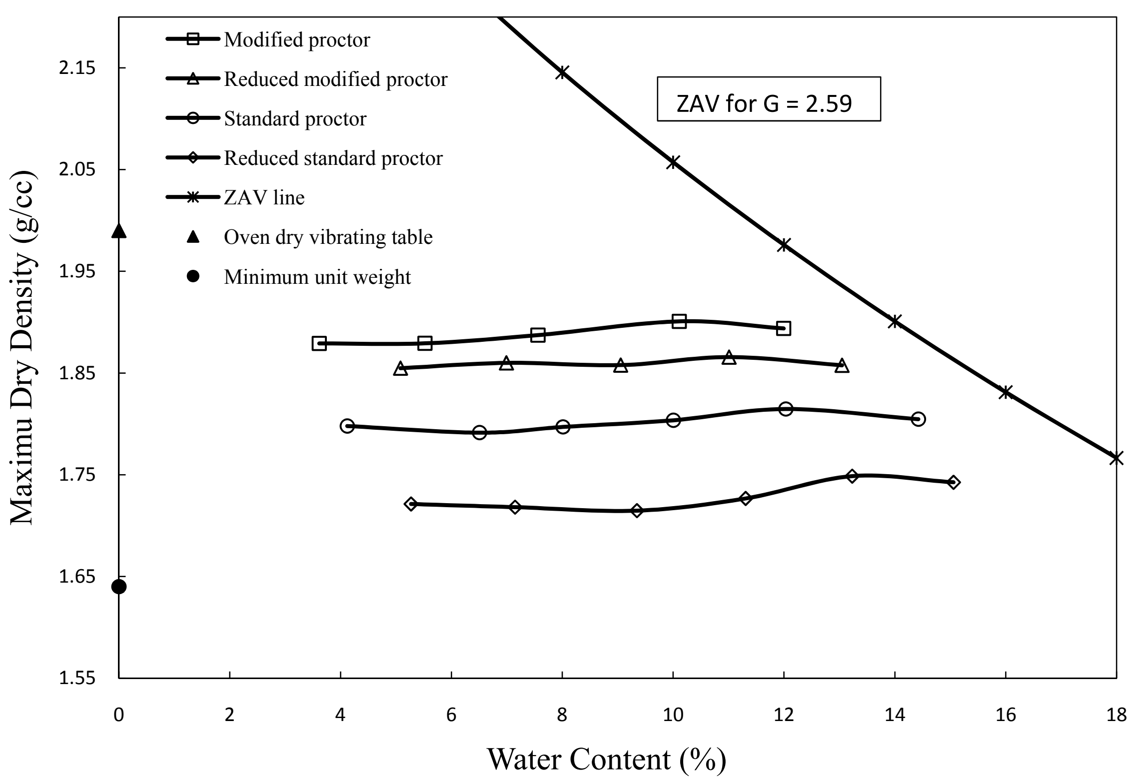

Figure A-43: Compaction results of Sample -43

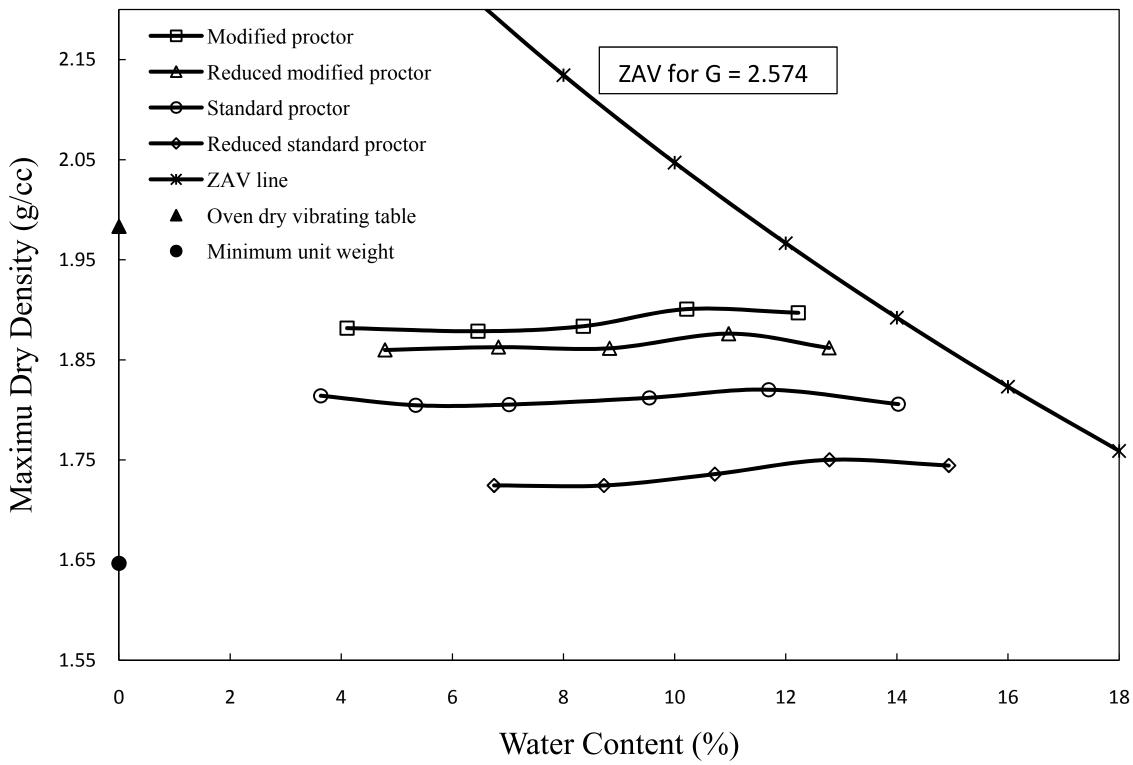

Figure A-44: Compaction results of Sample -44

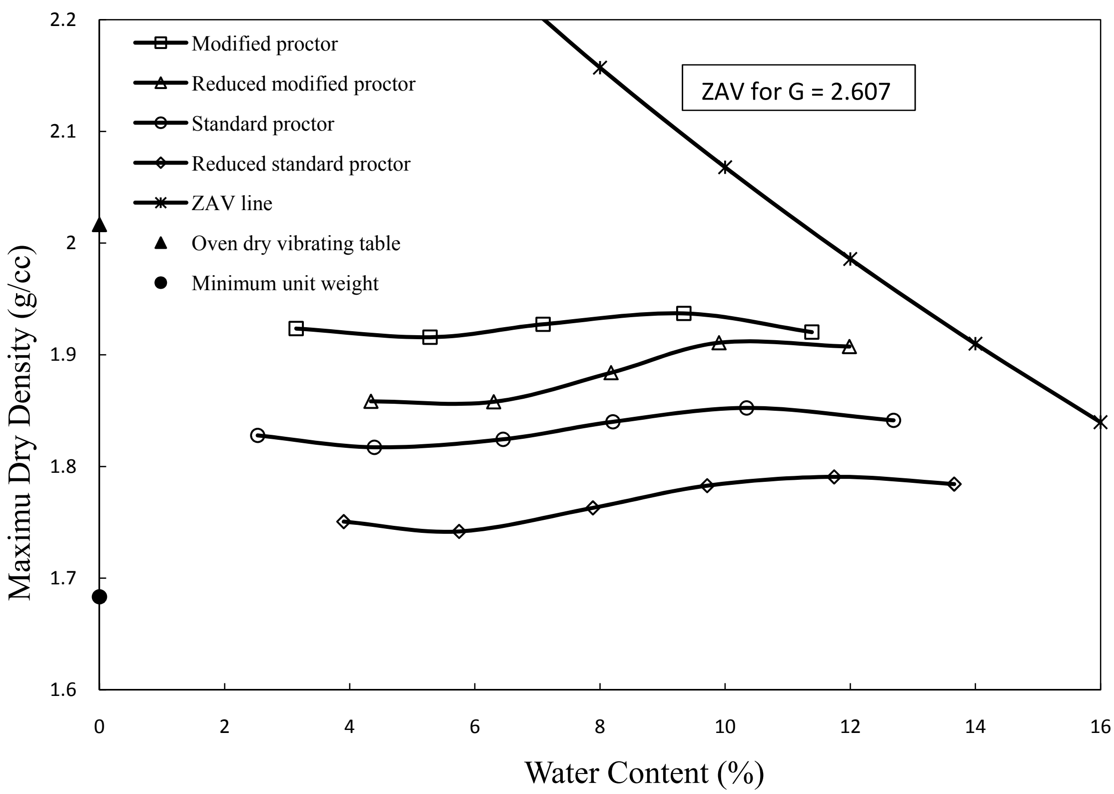

Figure A-45: Compaction results of Sample -45

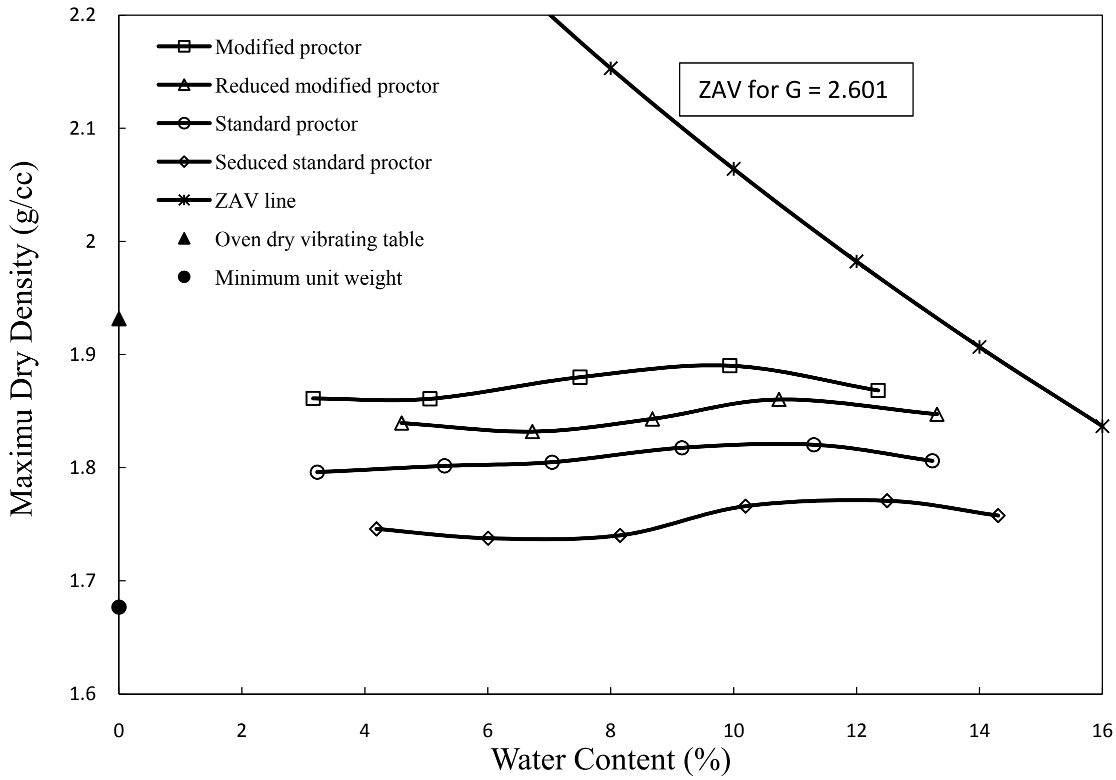

Figure A-46: Compaction results of Sample -46

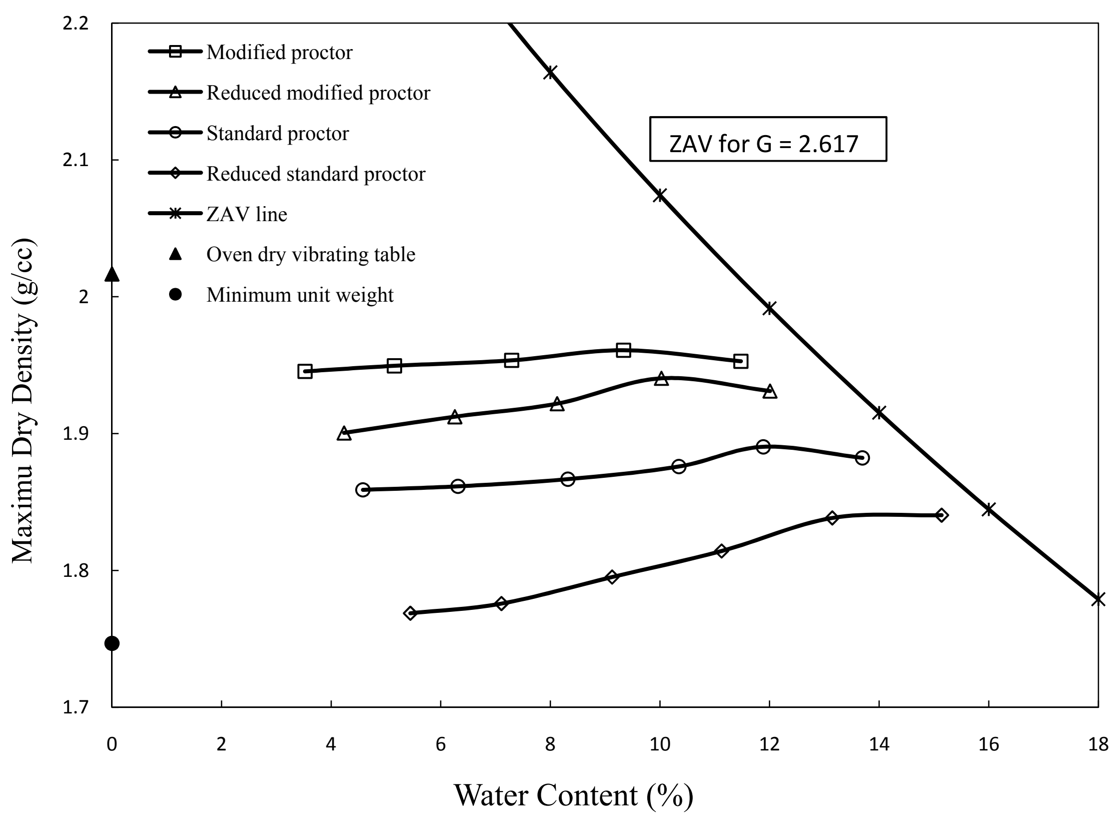

Figure A-47: Compaction results of Sample -47

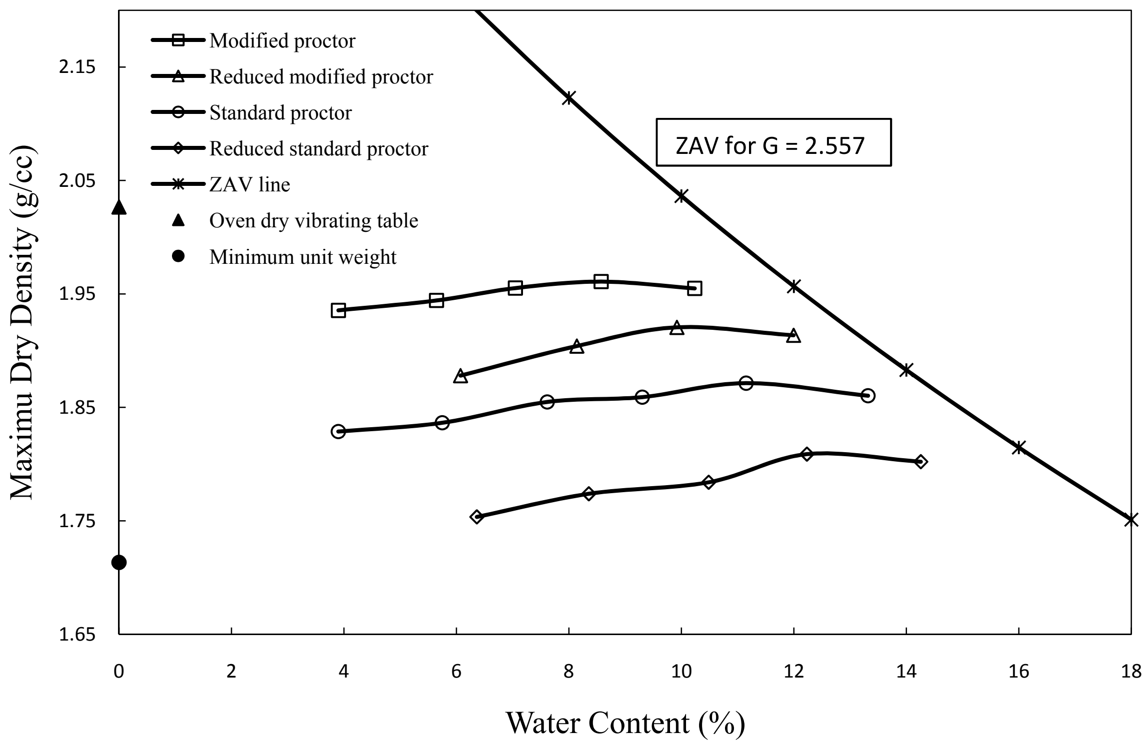

Figure A-48: Compaction results of Sample -48

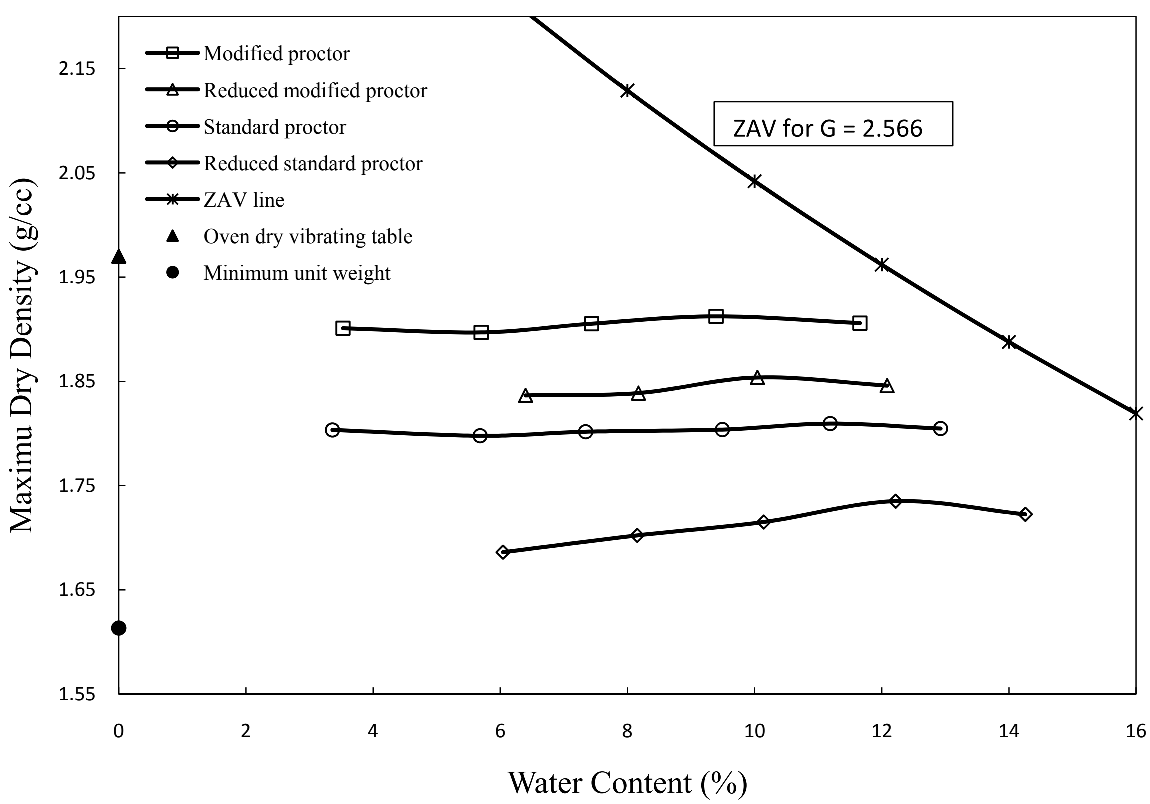

Figure A-49: Compaction results of Sample -49

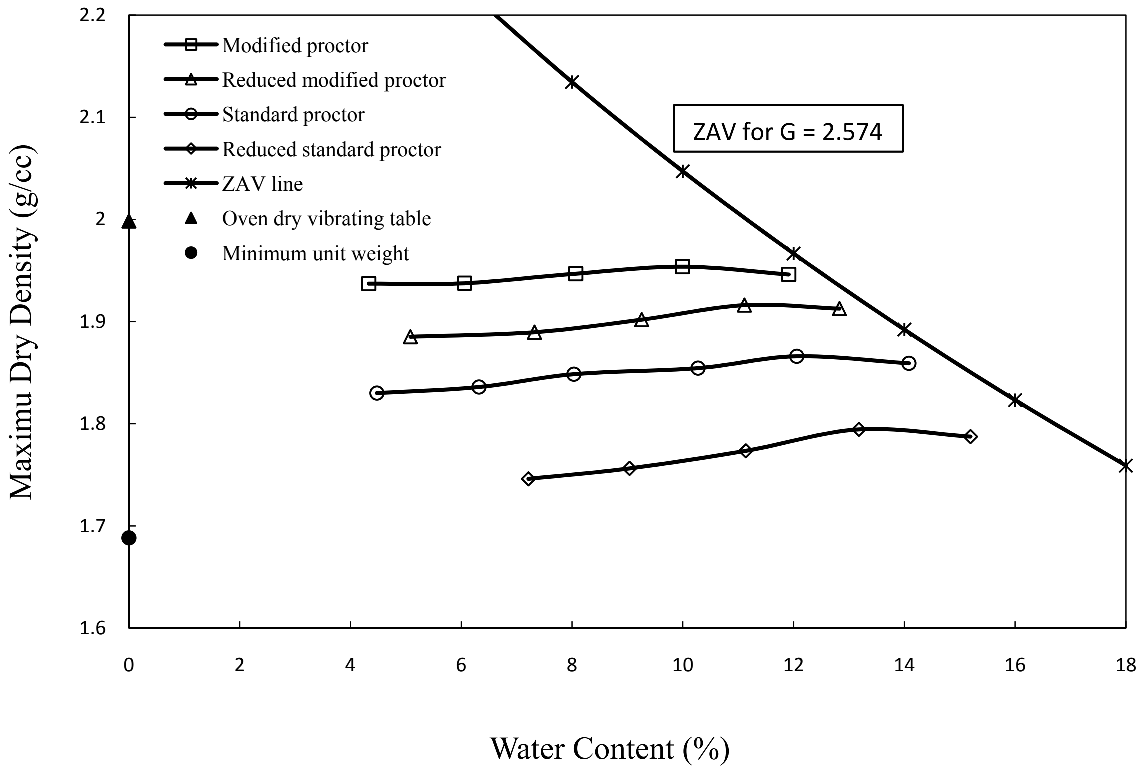

Figure A-50: Compaction results of Sample -50

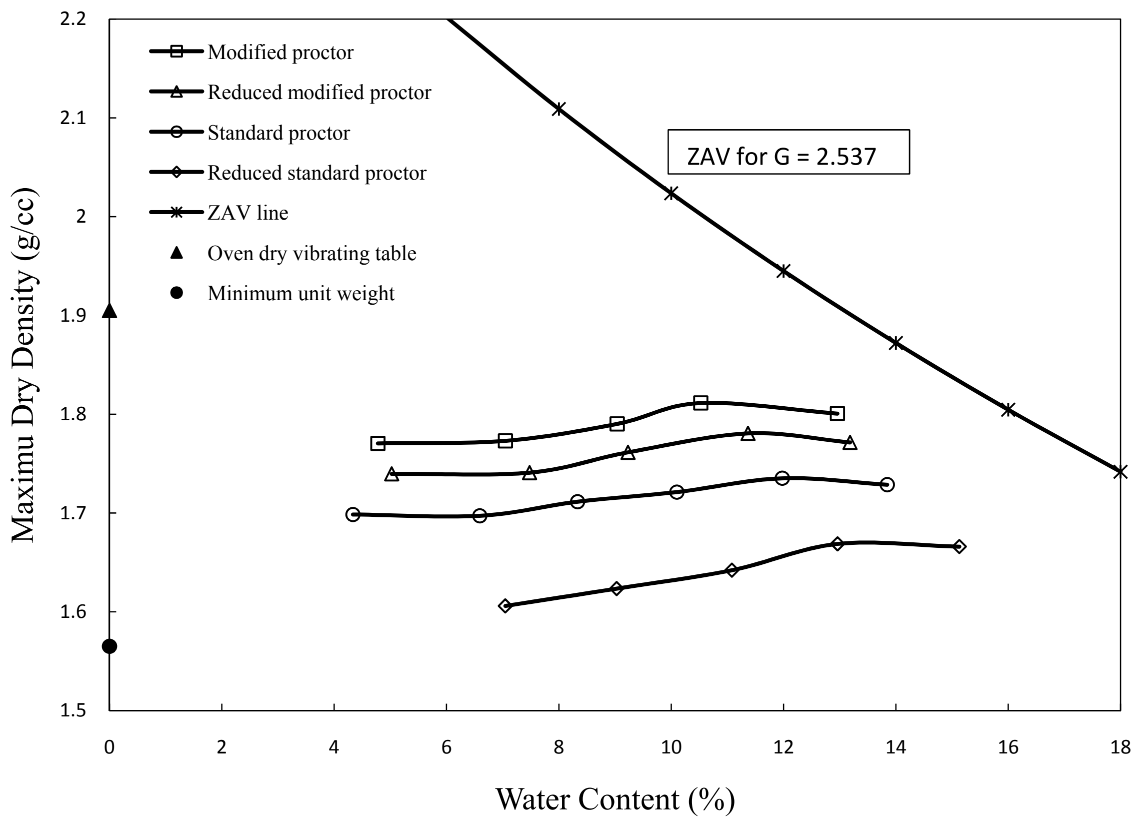

Figure A-51: Compaction results of Sample -51

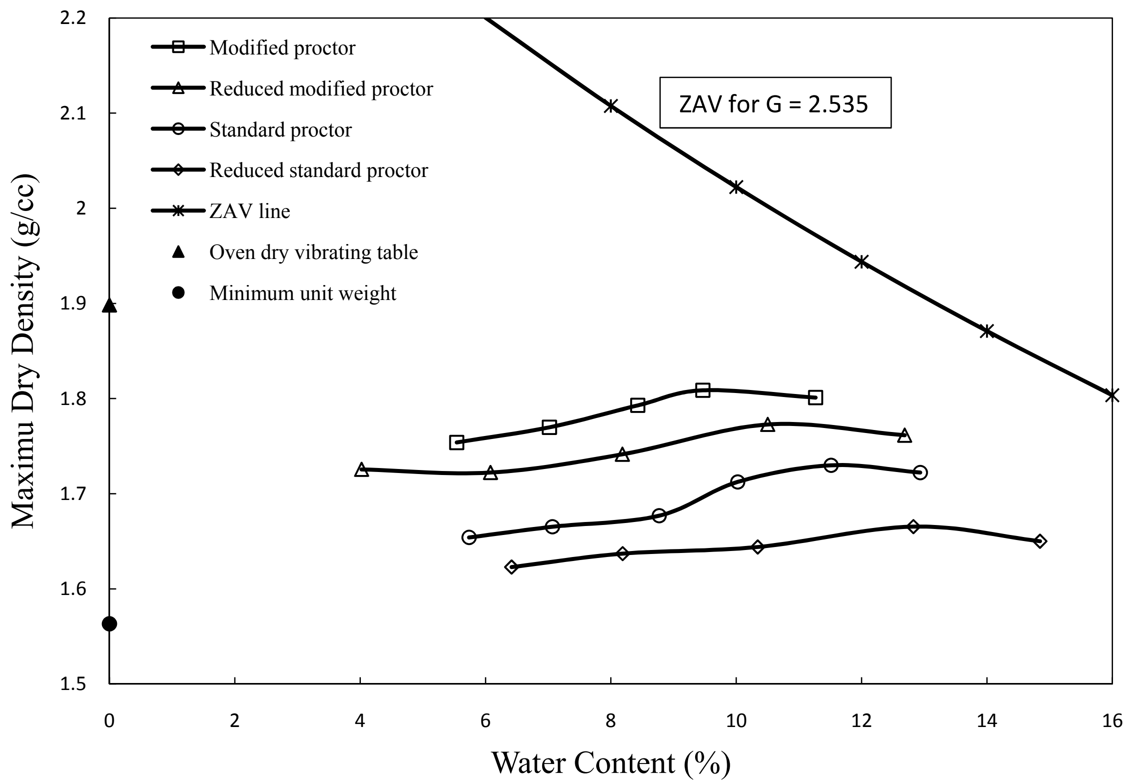

Figure A-52: Compaction results of Sample -52

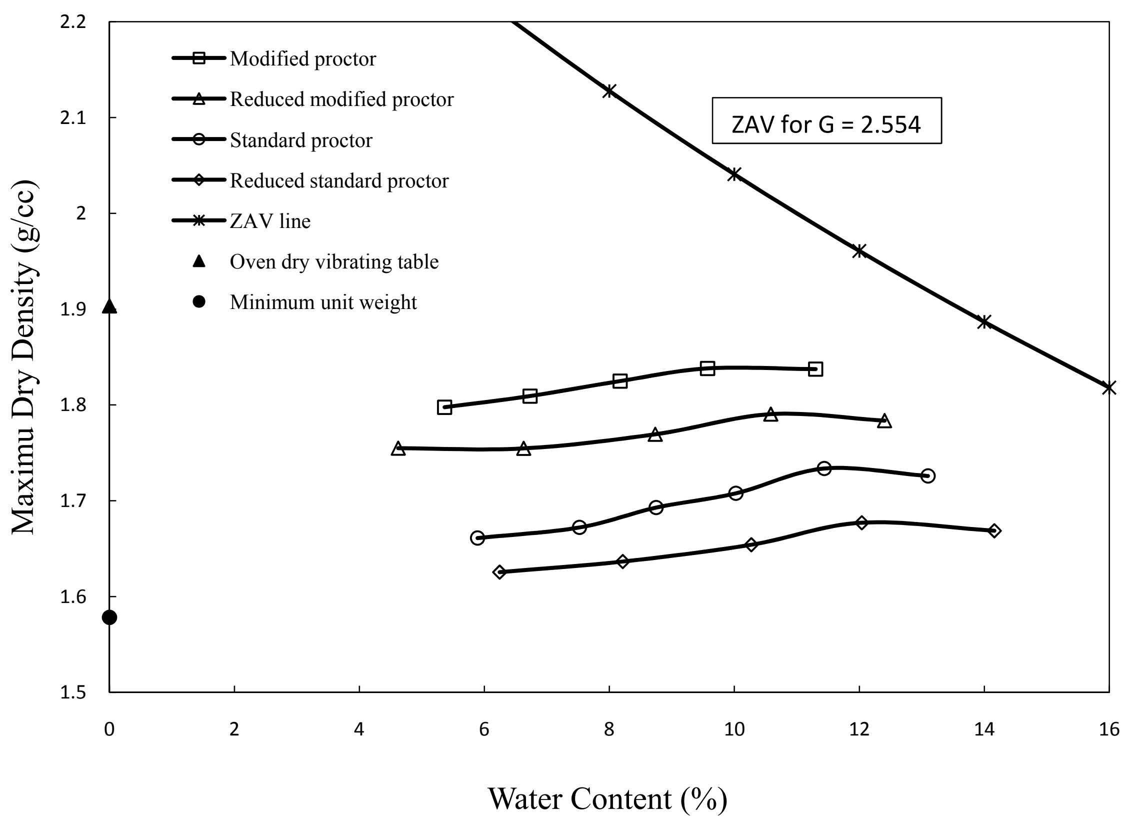

Figure A-53: Compaction results of Sample -53

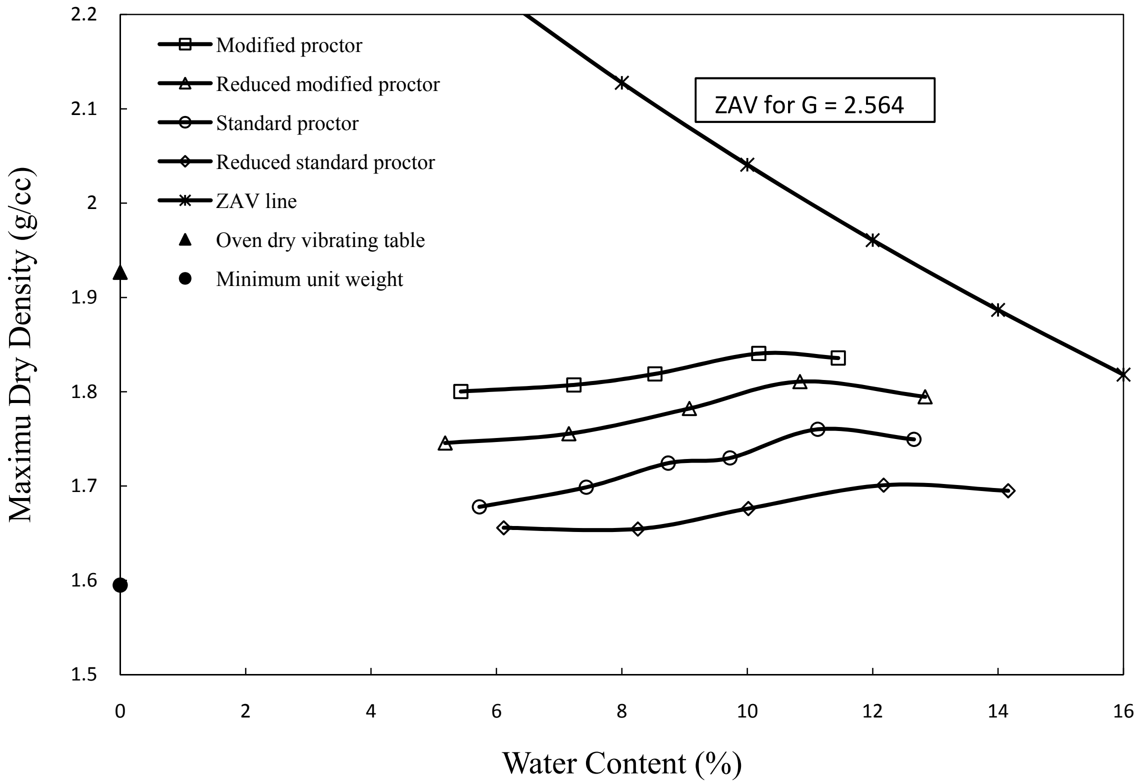

Figure A-54: Compaction results of Sample -54

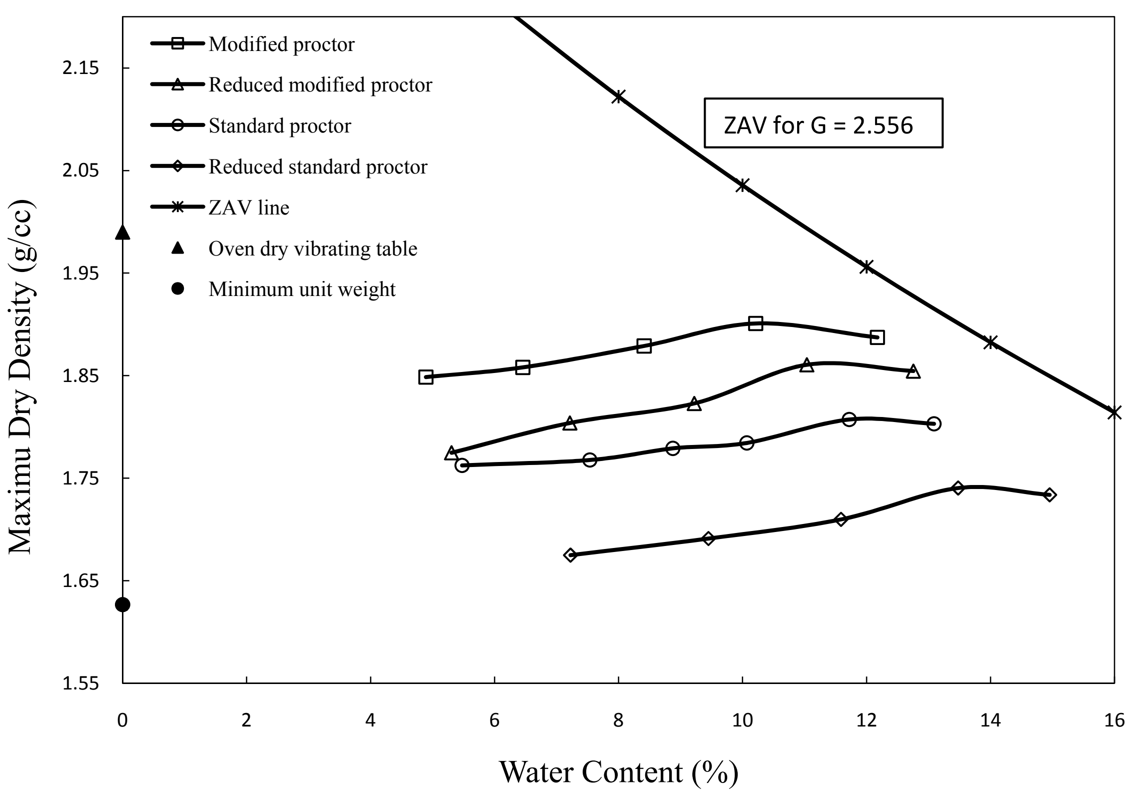

Figure A-55: Compaction results of Sample -55